Space Propulsion Synergy Team

A Guide for the Design of Highly Reusable Space Transportation

August 29, 1997

Final Report

Abstract

A Guide for the Design of Highly Reusable Space Transportation was developed to provide designers and decision makers a means for focusing key factors and relationships so that the resulting product is highly reusable, very responsive, safe, dependable, operable, reasonable in acquisition costs, and definitely affordable. The intent is to aid in strategic decision making. The guide deals with the many variables that go into providing an affordable, highly reusable Space Transportation System and brings an order of priority for improvement to each along with a descriptive understanding of each factor. These factors are called design and program features and benchmarks are provided where possible from existing systems. The desirable features have been developed from a combination of lessons learned in Shuttle, a bench marking approach, previous studies, a rigorous top-down methodology, and the experience and insights of team members. The consideration of these actual design features is important in broad architectural studies to produce operability and acceptable recurring costs when operating a reusable space transportation system.

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Introduction

About the Design and Programmatic Features, and the SPST

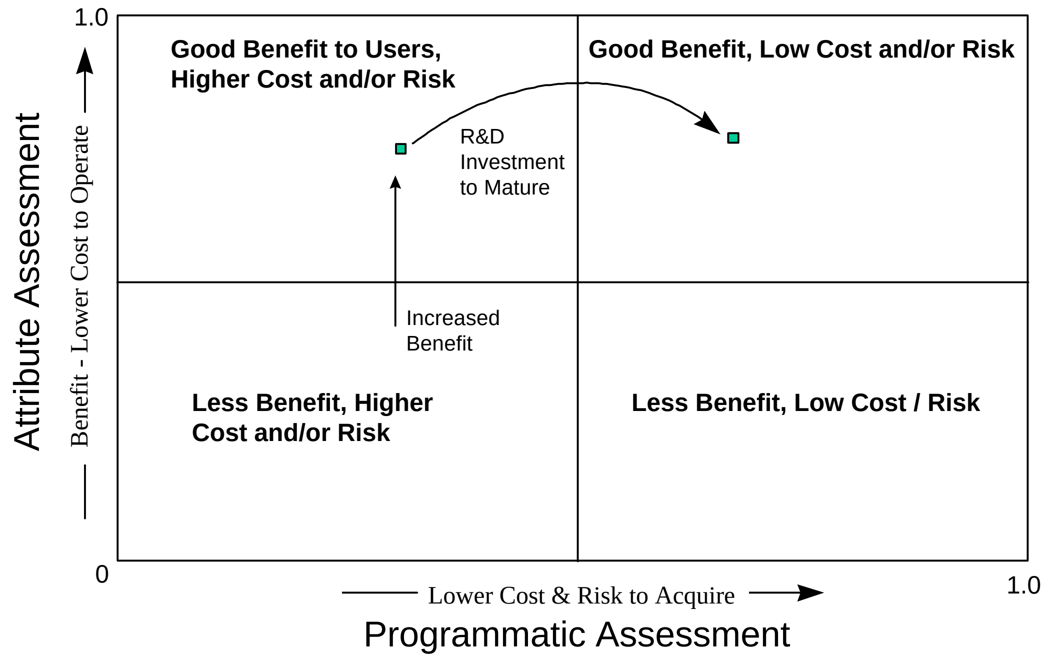
Customer demands for future space transportation systems include much greater affordability, responsiveness, dependability and dramatically lower life cycle costs including acquisition costs and research and development costs and risks. The purpose of this "Guide" is to provide a prioritized, high level set of design and programmatic features against which future space transportation systems may be evaluated to determine their degree of improvement over current systems and their ability to satisfy these customer demands. The guide may be used by a concept developer, a program manager, a technology developer or by designers at a total vehicle architecture level.

This guide was developed by the Space Propulsion Synergy Team (SPST) as part of its support to the Highly Reusable Space Transportation (HRST) project activities. The Space Propulsion Synergy Team (SPST) is a broad based group of diverse individuals from NASA, industry and academia, which has addressed in past and current efforts the direction of future space transportation systems and technology. The involvement of key backgrounds and areas of insight in the SPST has been an integral part of understanding and prioritizing areas for improvement.

During the past several years that the SPST, previously identified as the SPSG, has been active, they have developed and applied an effective process for comparative assessment of candidate space transportation systems and technologies. The process utilizes the strengths inherent in a team with diversified backgrounds and expertise; and the basic principles of a highly credible approach known as Quality Function Deployment (QFD). This approach assures that there is a direct link between the space transportation system capability and characteristics/attributes, and those required by the "customer".

Most important, this approach also includes the development and definition of "measurable criteria" to be utilized in assessing the degree to which a system concept or a technology enhances the system characteristics/attributes desired by the customer. These "measurable criteria" are presented in this guide and constitute the principle aid in the definition and design of an HRST or any advanced space transportation system.

However, it was realized that the system concept with the most attractive attributes and hence the greatest long term payoffs can lose support when programmatic constraints are tight. National space policies, international agreements, schedule, budget, availability and maturity of technology are a few of the examples of these “programmatic constraints”. Therefore, the SPSG devised a dual assessment and prioritization system that balances these two driving forces. A graphic visualization of the process is shown below. This approach enables decision makers to make decisions based on knowledge of both the long term strategic payoffs, “desired attributes” and the individual projects “programmatic constraints”. The later are subject to short term changes, but once the long term strategic payoffs, “desired attributes” are established, they remain quite stable.



An architecture with low programmatic cost/risk and a high impact on the attributes is most desirable

The stability of the “desired attributes” or long term benefits, in a transportation system has been thoroughly demonstrated over the past several years by the SPST and other organizations/groups. The SPST (SPSG) has developed and prioritized the desired attributes in a space transportation system several times, each time with a different group of individuals with consistent results.

Also, these sessions were in support of several different advanced space transportation programs. They included a follow-on exercise for the Access to Space studies and support of the RLV project definition and technology plan. Both of these activities utilized the process previously developed and exercised by the SPSG. The definition and prioritization of the required system attributes that resulted from each of these exercises were very consistent with those previously developed and were also consistent with those recently formulated for the HRST.

There have been other activities using the same basic process, notably several initiated by the USAF, but including industry and NASA participation. These activities also resulted in the identification and prioritization of required/desired space transportation system “attributes” that were very similar to those presented in this guide.

This dual prioritization approach is addressed in further detail in the next section of this report as are the definitions of the programmatic constraints.

Although the focus of the information provided in this guide has been within the context of the Highly Reusable Space Transportation (HRST) project, the applicability is to any future reusable systems seeking to improve over a current system such as Shuttle.

The features or criteria around which this guide is organized must be considered as a whole. If a future space transportation system improves or not on any one particular feature is not as important in determining merit as whether it improves or not on the majority of the significant features. A full understanding of future systems in regards to this guide is considered crucial to understanding a sense of direction for improvement as well as an understanding of the relative merits of systems competing for further development, acquisition and eventually operation.

Critical Information for Decision Making

In determining what information and data is most crucial to the decisions involved in defining, designing, and providing a market driven HRST system for the future we need to first identify that market, the customers, and clearly understand what they want in, and demand of, a space transportation system. However, in addition to the "customers" who will eventually pay for the services of a space transportation system, there are several other organizations / individuals who will be major players or "stakeholders" who must be fully considered and satisfied if a proposed space transportation system enterprise is to be successfully marketed and profitably operated. Including the paying customers, the stakeholders are:

1. The financial investor who will provide the capital for the development, acquisition and initial operation of the transportation system. He will demand a reasonable return on investment. It is possible that the investment may be divided into these two parts:
   - Capital for the design, development, and marketing of the transportation vehicles to be utilized in the operation of a space transportation system, for example a "United Spacelines".
   - Capital for the operator to acquire vehicles, facilities, and support infrastructure to start operations of a "United Spacelines."
2. The User or Payload Customer who will pay the operator for the transportation services of cargo and personnel in space.
3. The Developer and Producer of the space transportation vehicle which will be procured and utilized in the operation of a space transportation system. This includes the critical selection of the vehicle concepts which best satisfies all of the transportation system desired attributes and the design, development, certification, and production of the vehicle.
4. The Transportation System Operator of a "United Spacelines" who will acquire, establish and operate the transportation system as a profitable, business enterprise. This transportation system operator is a customer of the vehicle developer and producer.
5. The federal, state and local governments representing the general public, each play several important roles which must be addressed by both the system developer and operator.
   - The role to be played by the federal government is still evolving; but it is expected to be patterned after the role the federal government has developed with the airline transportation industry. The major elements are:
     - National policies to foster affordable, safe, reliable space transportation.
     - Provide development and demonstration of advanced technologies.
     - Assure public safety which is manifested in "spaceport" certification, launch permits, reentry control, and eventually space vehicle certification.

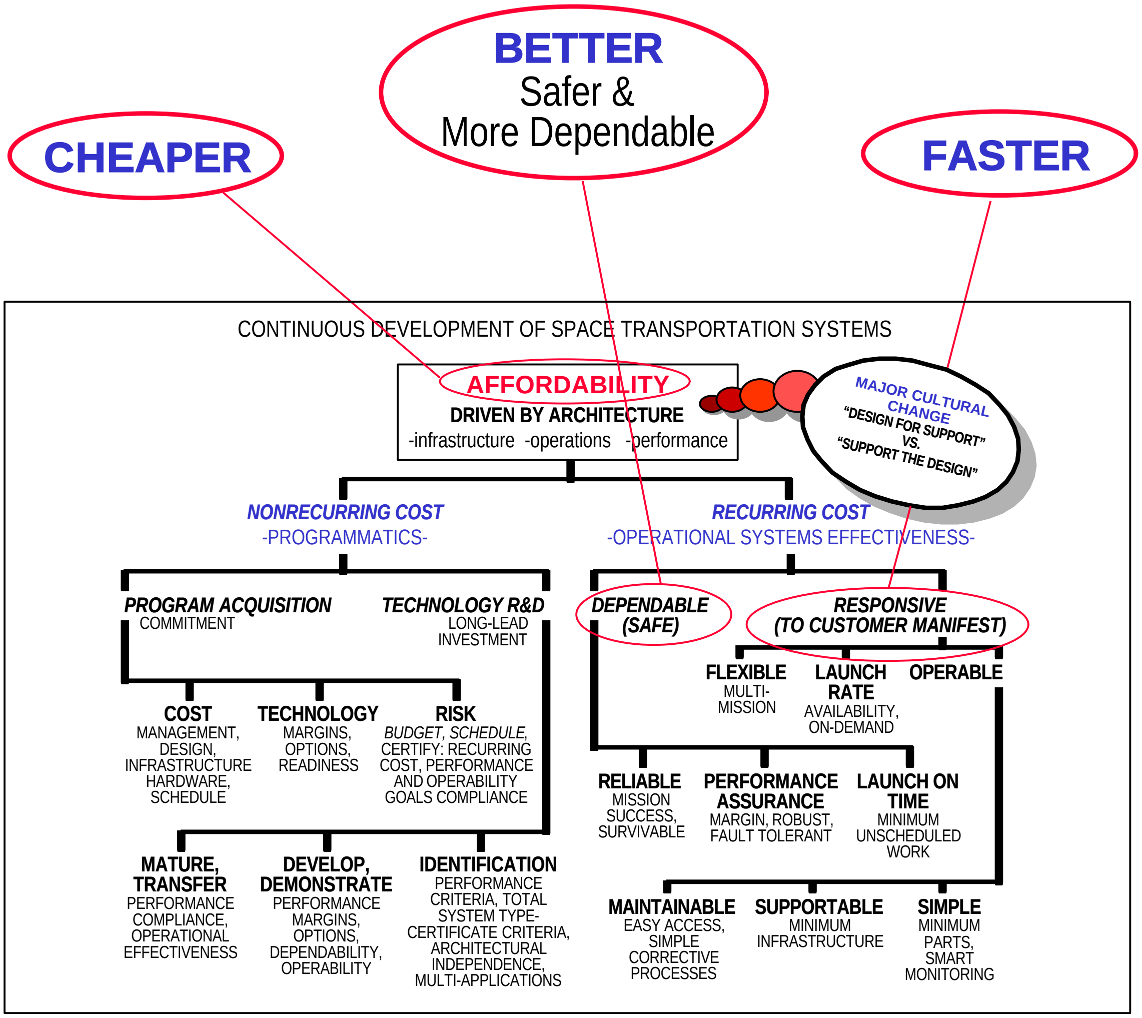
  - Negotiate, ratify, and enforce international agreements and treaties of space transportation operations.
  - Environmental control - ground, air and space.
- The state governments are interested in the potential economic benefits, development of new jobs, and the safety and environmental consequences of spaceport operations in their or neighboring states. They may be financial and political supporters or adversaries, and may be involved in support infrastructure, financing and development as needed.
- The role of local governments, again using the model of airline transportation systems is expected to have the following elements:
  - Investment and operations for fees of a spaceport similar to the relationship of a municipal airport and airlines.
  - Tax structure and incentives.
  - Support infrastructure financing and development of roadways, power supply, communications, etc.
  - Motivated by economic growth.
  - Constrained by environmental and safety concerns. The general public, taxpayers, will be concerned with many of the issues and decisions involved in establishing and operating a spaceport and need to be brought into the decision process as early as possible.

The purpose of outlining the major organizations and the role they will play in establishing and operating an HRST system of the future is to help the reader understand how and why this design guide was developed and how it may be helpful to designers and decision makers.

In developing this "Guide for the Design of HRST Systems" the "paying customer" and each of the other four stakeholders needs and demands were considered as requirements to be satisfied in the best manner possible. Particularly, the Commercial Space Transportation Study[8] has recently examined potential markets and associated needs to spur these markets. In the process used to accomplish this, the SPST divided the overall requirements into three categories:

- <u>Functional performance</u> of the transportation system such as capability in terms of payload or destination.
- <u>Desired attributes</u> of the transportation system (essentially demands of the customers) such as safety, affordability, dependability, or flexibility.
- <u>Programmatic constraints</u> of the transportation system such as cost, schedule, or risks associated with the design, development and implementation of the system including infrastructure.

The following chart focused on affordability shows the relationship of these categories and places them in two groups. The one group (desired attributes & functional performance) is described here as *recurring cost* or operational effectiveness and the other group (programmatic constraints) is described as *non-recurring cost* or programmatics. This group is further broken down into program acquisition (commitment) and technology R&D (long lead investment). The technology cycle is required when the technology readiness and risk from performance and operability goals compliance are not satisfied. Therefore, the key to achieving the objective of space transportation systems affordability is brought about when and only when the program acquisition criteria are properly met (technology margins, options, readiness, and full compliance of performance and operability goals can be achieved).



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FUNCTIONAL PERFORMANCE

The functional performance requirements used in the QFD process were basically those defined in the HRST project guidelines. The performance requirement was to deliver 30,000 lbs +/- 10,000 lbs to a 100 nm, 28.5 degree inclination orbit. A candidate transportation system (HRST) must provide credible evidence, system design and performance data to prove that it can satisfy the functional requirements.

In order to make a reasonable assessment of the potential of a candidate transportation system meeting the functional performance requirements there is a critical level of conceptual design data and performance flyout trajectory data that must be available. Since the concepts currently being considered for HRST include several variations and combinations of air breathing and rocket propulsion systems the design and performance analysis data must include critical parameters appropriate to these concepts. This data should include key aerodynamic characteristics of the vehicle such as the lift and drag coefficients as a function of altitude and Mach number, engine maps giving thrust and propellant flow rate as a function of altitude, Mach number and equivalence ratio, detailed breakout of component weights and a description of the force accounting system. The underlying data base for the engine maps should also be included in the data. This would include inlet compression efficiency, inlet air capture ratio, mixing combustion and exhaust nozzle efficiencies where applicable.

The section in this guide “Verifying Functional Requirements - Performance” further expands on information relevant to the performance aspects of an HRST, such as an air breather. For purposes of this guide and the initial work of the SPST, it should be noted, however, that the focus has been principally on the desired attributes and programmatic constraints of future concepts.

DESIRED ATTRIBUTES

In addition to meeting functional or performance requirements a candidate space transportation system must be evaluated in accordance with the degree to which it provides the attributes or features most desired by customers. These were identified by the QFD process as follows:

Affordable / Low Life Cycle Cost Low Recurring Cost Low Cost Sensitivity to Flight Growth Operation and Support Initial Acquisition Vehicle/System Replacement **Dependable** Highly Reliable Intact Vehicle Recovery Mission Success Launch on Time Robustness **Environmental Compatibility** Minimum Effect on Atmosphere Minimum Impact all Sites **Public Support** Benefit GNP Social Perception	**Responsive** Flexible Capacity Operable Vehicle Health Management Ease of Vehicle/System Integration Maintainable Simple Launch on Demand Easily Supportable Resiliency **Safety** Vehicle Safety Personnel and Public Safety Equipment and Facility Safety

These transportation system attributes were prioritized according to a combination of the importance to the customer, where we are today in space transportation, and how much we need to improve. Note that the lower level does not mean less important. Rather, it indicates that in view of current transportation system characteristics the need for improvement there is not as great.

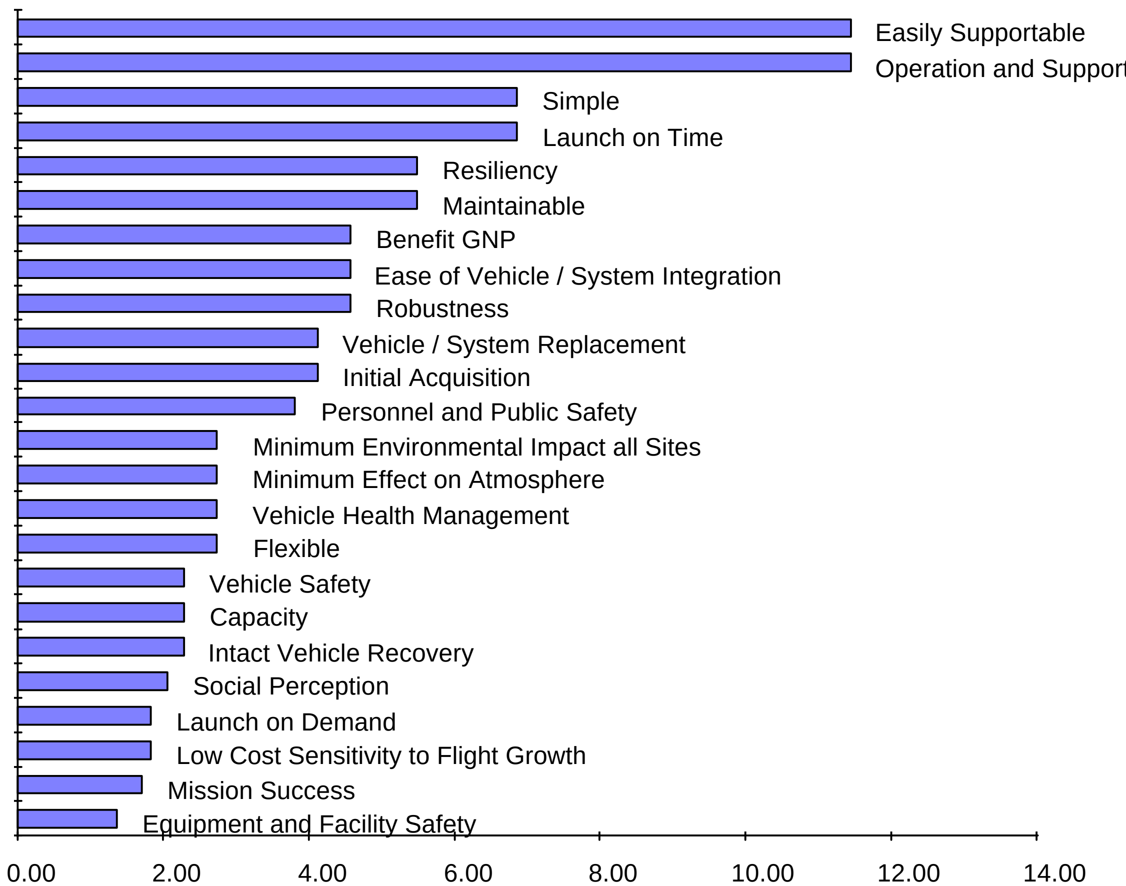


Figure A. Attributes of a Reusable Space Transportation System

However, it is very difficult for a transportation system decision maker or designer to respond to desired attributes, such as highly reliable, flexible or maintainable. Therefore, the next step in the process used to develop this guide was to identify measurable criteria that correlate with, such as have a positive impact on, the desired system attributes. There were many measurable criteria (64) identified. To aid the system definition and design decision process they have been prioritized in accordance with the degree of impact they have on the desired attributes. These are shown in Figures 1, 2 and 3. Each of these measurable criteria is addressed individually in this guide. Each of the highest criteria is a design feature that significantly impacts many of the desired attributes, particularly affordability, safety, dependability and operability.

In other words, the incorporation of design features, particularly those in the top 20 will have a positive impact on many of the attributes that the customer desires in a space transportation system. This relation of the design criteria and the desired system attributes and sub-attributes is shown on the following page.

Each of the systems major attributes and sub-attributes on the left have been connected to a box or boxes containing those design features which if incorporated in the system design would have a positive, beneficial impact on the desired attributes.

It may be noted here that the design criteria are divided into two groups. In the first group the desired direction is to minimize (minimum number). For example a minimum "number of potential leakage / connection sources" will have a significant positive impact on several of the desired system attributes. In the second group the direction is to maximize (maximum number). For example a maximum "number of components with demonstrated high reliability" in an HRST system will have a major impact on affordability (operations and support) and dependability (intact vehicle recovery, mission success and launch on time).

The highest priority (top 20) criteria, if manifest in a design with the desirable directions of improvement, will obviously have the greatest positive influence on the desired attributes. Therefore, <u>information and data on these top 20 criteria are most critical in any decision making process</u> that will define the most marketable transportation systems and choose among alternative design concepts.

Unfortunately, in the initial phases of the decision making process regarding future, next generation transportation systems, only top level information or data is traditionally available. In exercising the QFD process using the measurable criteria (Figures 1, 2 and 3) it was found that information on many of the top 20 criteria was not available even from transportation system studies that had been completed. In other words a different type of system information was required by a large number of measurable criteria. Referring to the description of levels shown below many of the criteria required data at Level 2 and some at Level 3.

Level 1 - Transportation System Concept Definition. This includes a sketch of the system and a functional description, performance analysis, preliminary mission trajectory and weight estimates.

Level 2 - Transportation System and Subsystem Description. This includes sub-systems configuration and functional descriptions including weight estimates. This includes propulsion, avionics, thermal protection and power generation definition.

Level 3 - System Preliminary Design Review. Information and data normally included in a PDR.

To correct this situation some level 2 subsystem description and data must be developed in the initial phases of advanced system studies. This is necessary in order to provide the critical information required by the top 20 criteria. This requirement needs to be communicated to the technical community involved in advanced transportation system studies and analysis.

Again, to assess future operational scenarios it is necessary to answer questions for which information is not often traditionally available before decision making processes such as funding distribution. "How often will it fly and for how much and why?" is a question the answer to which begins by addressing the criteria in this guide. This is not entirely a novel conclusion:

> *Only the direct hardware driven costs, about 32 percent of the Space Shuttle Program Budget, were addressed by the study. Current operations cost accounting methods were found to be inadequate for accurately determining the savings from subsystem improvements. The NASCOM was not designed for estimating modifications to existing systems and there are only limited tools available for estimating space flight operations costs.*
>
> From the NASA Access to Space Study, Summary Report[14]
> OSSD, NASA HQ, January 1994

PROGRAMMATIC CONSTRAINTS

The identification of the transportation system design features that will benefit (have a positive impact on) the desired system attributes was addressed in the previous section. The other dimension that must be addressed in any decision making process involved in the definition and design of an advanced space transportation system is the programmatic constraints. These are factors such as schedule, cost, risks and investor incentive in a given market environment. Again, in the QFD process that has supported this guide, measurable criteria were developed and prioritized. These are shown in Figure 4. Adequate information on these program criteria is as critical to strategy as the design features based on desired system attributes.

Our ability to acquire the critical information and data on schedule, costs, technical risks and so forth met with many of the same problems as were addressed in the previous section on desired system attributes. The necessary data is not readily available in the initial phases of transportation system studies and conceptual designs. It will be necessary to proceed to Level 2 in some cases to obtain it. For example, the number of technology breakthroughs required for successful development of a particular concept may require definition of major sub-systems.

It should be noted that in contrast to the stability of the desired attributes and the related design features in this guide that the program constraints may be expected to vary far more over shorter periods of time for several reasons. Global or national economic change, international competition and political scenarios may all significantly impact program considerations. This further emphasizes the need and value in defining the desired attributes and related measurable criteria or design features since they are the foundation of a technical strategy that can be expected to focus improvement efforts for the long term.

Beyond QFD - Key Questions for Decision Making

QFD (described further in “What is QFD?”) is not all inclusive in it’s ability to aid the decision making processes associated with large, complex technical projects. Sophisticated tool sets for analysis and modeling of future options from a technical, programmatic, performance and market perspective are required. One such project currently in work is called OSAMS.

Operations Simulation and Analysis Modeling System (OSAMS)
A Decision Support System

In order to develop a future space transportation system that achieves cost goals in the order of $200 per pound to low earth orbit, a systematic method needs to be developed to assess the impacts of various concept alternatives on cost and mission effectiveness. Specifically, an unbiased, user-friendly "tool" is required to allow program managers and developers to quickly assess the most effective areas to invest scarce resources and evaluate the potential impacts of these investments to the "life-cycle" and per mission cost of the system.

The NASA Advisory Council, in a letter dated 31 August, 1995, states that "Much of the cost for current launch vehicles is in the operations, launch rate, and support. For a reusable vehicle, this has proven to be the major driver (e.g., Shuttle). We recommend that a reasonably detailed economic model be developed that includes all the acquisition and operations costs; that is total life cycle cost. Such a model would be used to evaluate contending RLV concepts. This should be maintained by an independent studies and analysis group to help guide future RLV decisions." Further the NAC adds, "From the outset, the RLV of the future should be designed as a operational vehicle."

These recent statements by the NAC are equally applicable to HRST (and other space programs) and strongly support the development of an independent, NASA in-house capability for operations/life cycle cost analysis. The development of a comprehensive operations simulator for use in the very early concept evaluation phase, as well as extensible to later phases, would be a major step in realizing this capability. This tool would provide program managers and developers a method of performing analysis on all elements of life-cycle costs. It would allow a unbiased and consistent means to evaluate competing alternative launch and operations concepts, evaluate the impact of proposed technologies, and provide insight into life cycle, development and operations costs.

OSAMS will provide managers and developers with the needed analytical capability described above. OSAMS will be a powerful, flexible decision support system that will enable managers and developers to gain insight to HRST (or other system) concepts and variations. OSAMS will provide this support through a computer based environment for the analysis of systems concepts and will aid the manager/engineer in both life and flight cycle evaluations of concepts through the use of interactive dialogues with the system engineer. These dialogues will be conducted through a display screen using windows and pull down menus using a variety of input devices that include keyboard, mouse, and function keys. Using these completed dialogues in combination with pre-defined OSAMS components, the system engineer will be able to describe HRST concepts through a series of documentation activities that describe mission models, flight vehicle concepts, vehicle ground processing concepts, payload processing concepts, and maintenance and refurbishment concepts. Using OSAMS tools the system engineer will transform these HRST elements into a dynamic monte carlo simulation of these combined elements and interactions.

OSAMS will support procedures for analyzing these statistically valid simulations in terms of life-cycle cost, and system performance. Life-cycle cost is composed of research and development costs, acquisition costs, operations costs, maintenance and refurbishment costs, disposal costs, and the associated cost of system failure. System performance measures includes both system and schedule reliability, facility utilization, payload delivery, and market competitiveness.

OSAMS will aid HRST developers in HRST program implementation planning. OSAMS analytical tools will include methods for calculating return on investment, and technical and program risk. OSAMS will also aids HRST developers by providing automated methods of performing sensitivity analysis on key concept and mission model parameters. OSAMS will provide a state-of-art environment where its modeling and simulation tools can be used individually or as a set of highly integrated tools for evaluating system concepts, aiding in the selection of alternative investments in technology to reduce operations and life cycle costs, and ultimately, in improving the operability of the resulting HRST system.

Margin Considerations

The amounts and the types of margin present in a vehicle design strongly impact the resulting transportation architecture. Two types of margin will be discussed; growth and technology margins used (and used up)[2] in design and development, and margins still present in the fielded system.

Traditionally, margin is used during the early stages of program design and acquisition as a contingency to allow for weight growth and growth resulting from addressing design uncertainties during development. This type of margin should always be present with the amount being dependent on the maturity and definition of the subsystems technology and the overall design. For example, in the Access to Space study[14] and the RLV studies which followed a weight margin of 15% was used on all subsystems, both vehicle and propulsion. The studies represented a new architecture (SSTO) using many unproved subsystems. Since the historical weight growth of the SSME engine was 14% and the engine had relatively low TRL's at the time the design concept was frozen, the use of 15% appears to be "in the ballpark" for experimental programs but questionable for HRST goals. All HRST design concepts should have this kind of margin included and defined. This type of margin should be included when trajectories are run to determine performance closure. All architectural concepts must include these margins to allow true concept comparisons.

The type of margin discussed above should always be present in preliminary concept designs but is not the type of margin that will increase the probability of reaching the HRST goals - very affordable space transportation, because this type of margin is, historically, always used up simply to make the design a reality. Also, note that historically past programs were focused on performance and not economics. Indeed, the choice of an appropriate number to use for this margin is based on finding what margin was needed in past designs.

The type of margin useful to achieving the HRST goals is margin built into the system, or subsystems, and not used merely to achieve the minimum necessary system performance. It is essentially the ability to operate the system, at least before using the margin to improve affordability, in a de-rated condition and still achieve the minimum required system performance.

The type of margin useful to achieving the HRST goals is margin built into the system, or subsystems, and not used merely to achieve the minimum necessary system performance. It is essentially the ability to operate the system, at least before using the margin to improve affordability, in a de-rated condition and still achieve the minimum required

system performance. Margin of this type is available to improve affordability and not merely to compensate for the uncertainties of development. This type of margin is considered in aeronautical transportation systems but up until now has not been adopted for aerospace transportation systems.

Four measurable criteria were identified for this type of margin: mass fraction margin, thrust (chamber pressure) margin, average specific impulse margin, and payload margin. Because each of these criteria correlated against a subset of the desired attributes, none of them individually rated very high (40/63, 44/63, 50/63, and 59/63 respectively). A single criteria measuring overall system margin was also considered and it rated very high. There are also many other subsystem margins that could have been considered, such as thermal management, fluid flow or current capacity, but they would have been too detailed in relation to the other criteria.

Mass fraction and thrust (chamber pressure) margin are directed specifically at the vehicle and the propulsion system respectively. Margin designed in for the mass fraction allows use of more robust components and structures, or higher safety factors on life limiting structure and components. This margin would also allow the use of heavier but more developed technologies in selected applications. All of these are reflected in planned and unplanned maintenance and life, which in turn affects inspections, logistics, facilities, and turnaround time, responsiveness and safety.

Thrust margin is generally related to operating rocket engines below their maximum design limit to increase operating life. This is thought to increase mean time between failures of the propulsion systems. For example, the theoretical mean time between failures of the Phase 2 SSME improves more than ten times if operated at a power level of 100% instead of 109%[19]. The improvement is related to decreased temperature, speed, and pressure environments within the engine and component operation away from the structural limits used when the engine was designed. Low cycle thermal fatigue limits are particularly impacted. In general, de-rating an engine significantly improves its life which allows less inspection, better predictability of failure (unusual conditions do not push internal environments beyond design limits), and less maintenance. All of which lower logistic and facility requirements and improve turnaround time. The cost of including a thrust margin is an essentially linear reduction in engine thrust / weight. Also in the area of the rocket engine start transition, the stresses traditionally exceed the steady-state conditions resulting in large operating life reductions and requirements for inspection and maintenance. Margin must be included here to cover transition by providing a softer start capability. For systems where performance is the main goal or where the mission is barely possible with expected engine weight, thrust margin may be a luxury; but for systems where operating cost is the main goal, thrust margin may instead be a necessity.

The criteria on average specific impulse margin is traditionally treated as essentially a technology uncertainty margin. It is aimed at those systems where a high specific impulse is predicted and is critical to the design, where there is a tight coupling between details of vehicle geometry and engine performance. Thus, this margin is more like the margins discussed at the beginning of this section which should be present in the preliminary design. The amount of margin should probably be varied depending on the degree of database available for the vehicle / propulsion system being studied. To the degree that the specific impulse margin is not consumed during development, it acts the same as a payload margin and could be used to avoid operations such as abort options like RTLS and TAL or other operations which increase infrastructure and add considerable operating cost.

The last of the four margins considered is a payload margin. This is essentially an overall system margin which can be traded to all subsystems if necessary. To strongly affect affordability, this margin must be maintained and not simply used as a weight growth margin during development. Besides allowing propulsion subsystem de-rating (i.e., lower thrust for the nominal payload), payload margin is usable after the system is developed for system additions targeted specifically to improve operations based on operating experience (without this margin this is not possible while still meeting the nominal payload). Additionally, payload margin produces the flexibility to respond to new demands and commercial opportunities.

In summary, any system with margins over and above the development margins will be more operable than one without margins because of subsystem operation at reduced design environments. This will in turn lower maintenance, logistics, and facilities requirements, while allowing targeted system additions to address remaining or newly discovered operability problems while still performing the required mission. The payload margin will provide flexibility to new business. The specific impulse margin will reduce operational infrastructure required for safe operation. These are the characteristics which produce affordable space transportation systems.

About This Guide - A Brief Description

The guidance contained in this document can be categorized as “design features” or “program features”. The design features are those which bear directly on the technical aspects of a concept. Program features relate to the management focus that brings about the implementation of the concept.

- Design Features: These are measurable criteria. A number may be assigned to these for current systems. For future systems a target may be set which is then the “design target”. The more improvement is made in each criteria the greater the correlation to meeting more vague, qualitative goals such as affordability of operation or high flight rate. These capture the recurring aspects of reusable space transportation systems.

- Program Features: These are measurable criteria. In general these present more of a challenge to baseline or set new targets for. These capture the non-recurring aspects of a reusable space transportation system.

Major characteristics of the guidelines are:

<u>Prioritized:</u>

The first 29 of the design features and the first 9 program features correlate very strongly to effectiveness and efficiency respectively. Effectiveness refers to results such as being low cost to buy and operate. Efficiency refers to how much was spent in time or money to get to that final product. The higher the rank (1, 2, 3, …) the more strongly the features correlate to qualitative “wants” such as low life cycle cost which includes low cost to develop, manufacture, buy and operate.

<u>Numeric:</u>

Numbers exist for where we are in many areas. Hence numbers may be assigned for how much we wish to improve.

<u>Directional:</u>

A sense of direction can result from assessing a future concept against these features. Relative merit can be assessed among multiple concepts. Assessing a set of design variables against these features will not result in quantitative life cycle cost estimates, schedule timelines or dollars per pound to orbit. The intent here is to assist in determining strategic directions for improvement which may then be more quantitatively assessed by implementing more detailed analysis, methods or models. This communication of practical engineering information can aid in focusing more formal requirements (Blair and Ryan 1992)[6].

More detailed subsystem understanding and iteration on the implemented results of QFD's, based on lessons learned, technology demonstration and product experience, are required to fully exploit the QFD method. In this way quality, meeting customer demands and growing markets, is built into the technology across many levels. From this approach, detailed relationships between features and costs in space transportation systems can eventually mature.

Document Format Description

- The format that follows for each of the **design features** is:

(#) Number of ______________.	States the design feature. Most of the measurable criteria can be directly manifested in a design. For a minority of the measurable criteria the feature is not directly a technical aspect of a system but rather relates to areas requiring emphasis.
Shuttle Benchmark: ___.	An estimate for the Shuttle program.
Derivation:	A brief description of the current situation and definition.
Level: 1, 2 or 3.	For a new concept a number for comparison relative to Shuttle may not be available until further definition is worked. Decision makers must try and make as many of the criteria as possible into information that is available early on in any decision making process. Ideally, all the criteria contained here would be "Level 1" information. 1 - Usually available early in the concept development and evaluation. 2 - Available as the concept becomes more defined. 3 - More detailed information that is available as the design matures to a preliminary design phase.
Visions of Improvement:	A description of how to improve on the criteria, what makes the criteria worse and other considerations.
Target for Improvement	How the feature can be targeted or interpreted for improvement.

- The format that follows for each of the **programmatic features** is:

Program Feature	Definition / clarification.

Figure 1: Prioritized Measurable Criteria

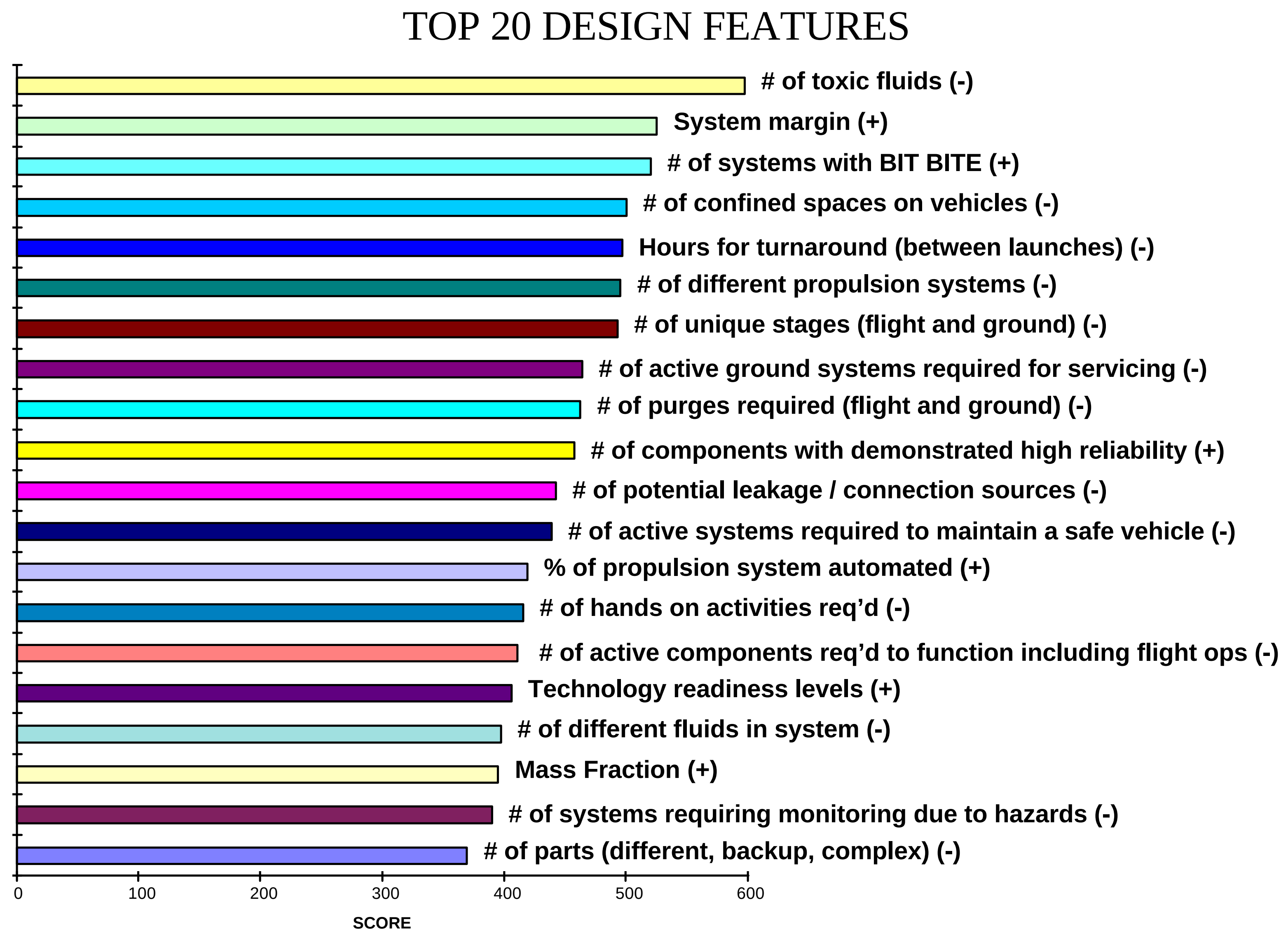


Figure 2: Prioritized Measurable Criteria

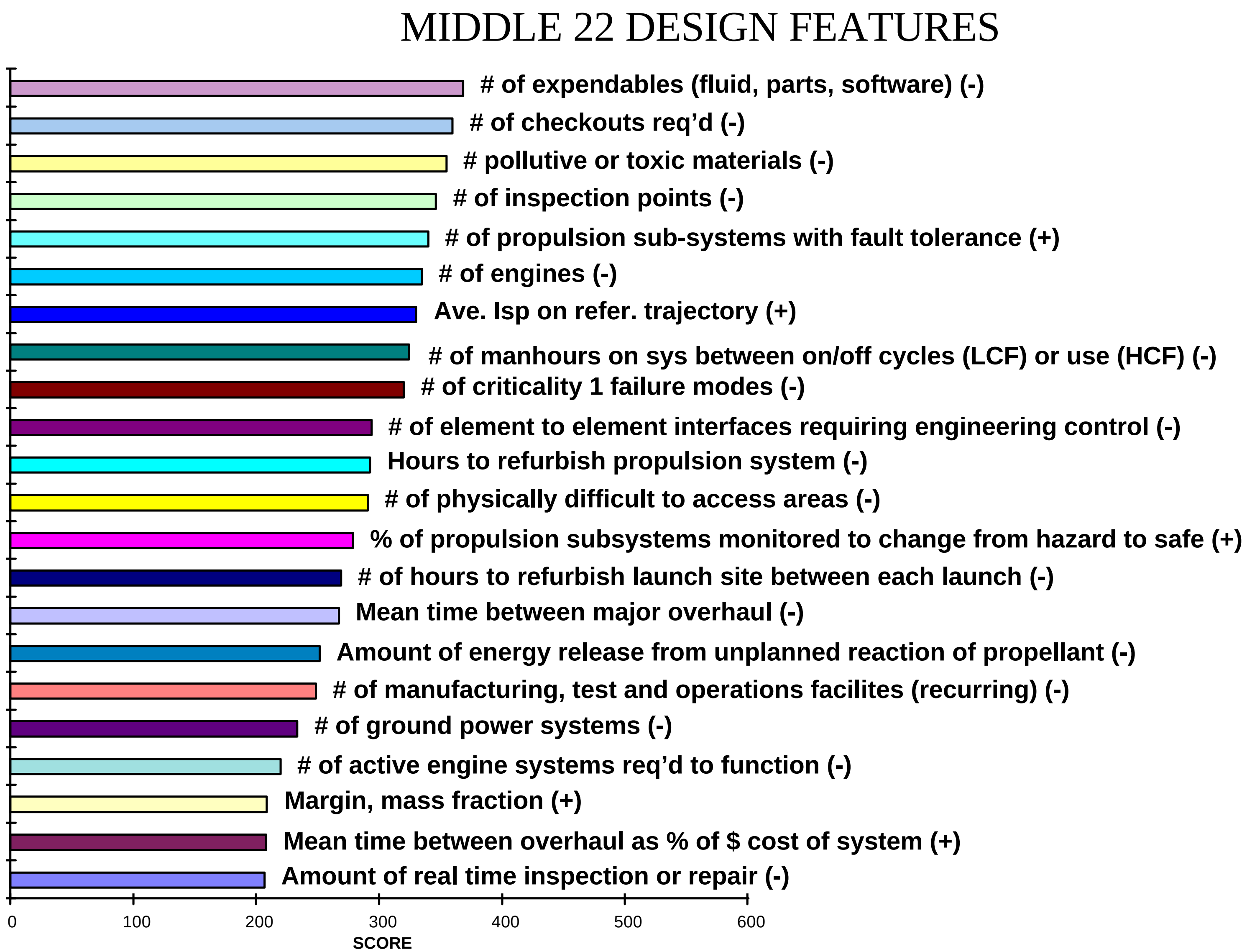
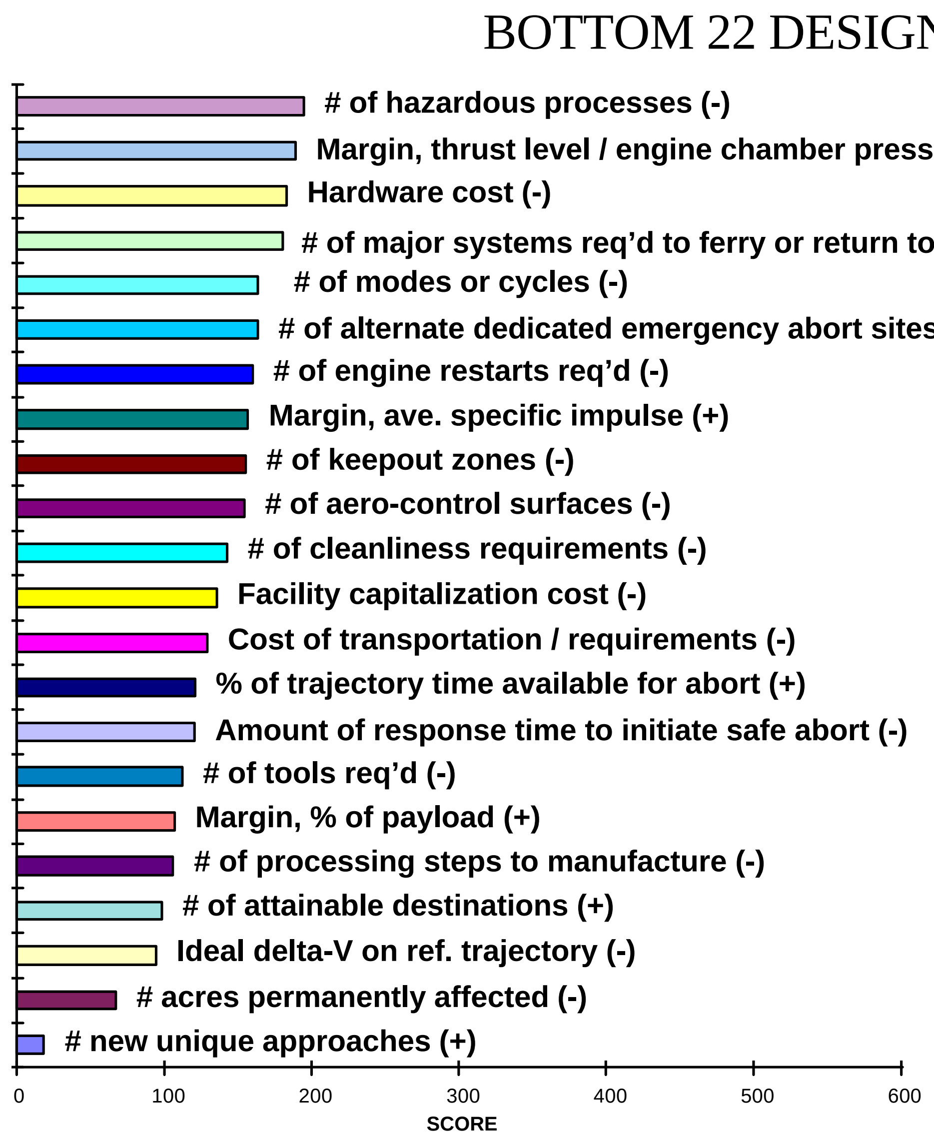


Figure 3: Prioritized Measurable Criteria



(1) Number of toxic fluids (reduce):

Shuttle Benchmark: 10 (majors only)

Derivation:

This criteria includes toxic fluids for both flight and ground operations. The number of different toxic fluids used in a space transportation system relates very strongly to recurring costs, such as operation of the system, and hence to life cycle cost and overall affordability. The correlation is also very strong to initial acquisition, the ability to launch on time, the degree of supportability and personnel and public safety. Public environmental concerns are also affected. Reductions in the number of different toxic fluids improves significantly in all these prior areas.

For Shuttle the major toxic fluids include:

- Hypergols (N_2O_4 and MMH) for OMS/RCS as well as hydrazine (N_2H_4) for auxiliary power units (APU’s).
- Hydraulic fluid for the actuation of aero-surfaces, landing gear and valves.
- Waterproofing agents (DMES) for tile thermal protection systems.
- Freons (3 types): R-21 for thermal management on board the vehicle (indirect and direct cooling of avionics, crew cabin, and fuel cells and warming/cooling of hydraulics on orbit); R-114 in the orbiter payload coolant loop as well as the ground coolant unit circulation module; and R-22 for the ground coolant refrigeration module after the ammonia boilers are turned off (pre-launch and post landing).
- Ammonia (NH_3) for thermal management (heat from the Freon-21 loops below 100,000 feet until ground cooling is turned on).

Other:

- CFC-113: Trichlorotrifluoroethane (Freon PCA, precision cleaning agent) for ground operations.

Toxic fluids such as the hypergols or waterproofing agents are significant contributors to the number of keepout zones around a system. This prevents other work. Costly infrastructure for SCAPE operations (protective suits and gear) is required for hypergols. For all the toxic fluids, including the hydraulic fluid or freon loops, operational affordability is driven by manpower intensive system verifications, mostly manual, such as leak checks, interface verifications, non standard payload interfaces, or verifications for air intrusion into hydraulic lines.

Level: 2 - Information is available on this criteria as the concept becomes more defined. However, this should be considered critical information required of any concept very early in decision making.

Visions of Improvement:

Basic improvements include the elimination of hypergolic fluids for auxiliary propulsion (both OMS and RCS) such as through the use of O2/H2 based systems. Further basic improvement would build on the prior plus address any toxic power sources such as hydrazine APU's. Candidates for power sources such as batteries may simply replace one toxic fluid and set of tasks for another. Higher density fuel cell type power sources may improve on this criteria but must consider thermal management of the power supply which relates to toxic fluids such as freons and ammonia discussed ahead. A whole picture of thermal loads and management is required in optimizing for power requirements, reducing toxic fluids and providing cooling of avionics or other heat generating sources.

Another basic improvement would be the replacement of hydraulic fluid actuation of aerosurfaces, landing gear and valves by the use of electromechanical actuators (EMA's). This conversion from a fluid to an electrical system is synergistic with the "number of systems with BIT / BITE (increase)", a top ranked criteria.

Further improvement would also eliminate the use of toxic waterproofing agents such as DMES for tile type thermal protection systems. Maximum improvement here assumes *elimination of the waterproofing task* and not just replacement of the toxic fluid DMES with a non-toxic.

Maximum improvement would address all the prior as well as thermal management systems for (1) avionics (or electronic equipment generating heat), (2) power sources (such as fuel cells on Shuttle) and (3) environmental control systems (passengers, A/C). All of these currently use freons which are either banned from production or are planned to be banned. This area is synergistic with the "number of active components required to function including flight (reduce)". Reductions in heat loads from avionics or increases in power source efficiencies could reduce some of the active (fluid) thermal management load requirements. The remaining heat loads as well as increasing passenger heat loads would have to be addressed via non-toxics to fully improve on this criteria.

Finally, ideal levels of improvement would have addressed all the prior as well as the use of toxic fluids in ground operations and recurring manufacturing operations such as the use of freon PCA in field cleaning or manufacturing processes.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be established with relative ease. Improvement may be measured relative to the number of toxic fluids for Shuttle.

For example, a design may target using only 2 toxic fluids, freon PCA and one low toxicity HCFC coolant circuit, almost an order of magnitude improvement over Shuttle.

Labor Type	APU #1 & #3 Propellant Service			APU #2 Propellant Service			
	No.	Duration	Manhours	No.	Duration	Manhours	TOTAL
Technicians (SCAPE)	4	10	40	2	6	12	
Tech. Backup (SCAPE)	4	10	40	2	6	12	
Quality (SCAPE)	4	10	40	2	6	12	
Quality Backup (SCAPE)	4	10	40	2	6	12	
Life Support	1	10	10	1	6	6	
Tech Support	1	10	10	1	6	6	
APU Console Engineer	2	10	20	1	6	6	
Quality Console Engr	2	10	20	1	6	6	
Personnel	22			12			**34**
Manhours			220			72	**292**

Table 1. Hazardous operations are one aspect of the major toxic fluids on Shuttle. This example for the Shuttle Auxiliary Power Units demonstrates high manpower requirements due to the use of hydrazine, a hypergol. SCAPE operations require keepout zones, preventing or displacing other work as well as making the operations themselves difficult due to bulky protective suits and gear. Source: Electric Actuation Technology Bridging Program[12].

(2) System margin (increase):

Shuttle Benchmark: Zero to low - indeterminate as of this revision.

Derivation:

- This criteria refers to that margin which is available in a fielded operating system. It is essentially the ability to operate a robust system in a de-rated condition while still achieving the minimum required system performance. This margin is not that which is used during development in expectation of weight growth due to uncertainties of design or technology.

This criteria correlates strongly to operation and support costs, reliability, flexibility, capacity, maintainability, ease of support and vehicle safety.

For Shuttle examples of lack of margin or negative margin (of this type, in the fielded system) include:

- Thrust levels at 109%, not 100% (or less)
- Engine removals every launch, not every 55 starts
- 7-8 launches per year, not 40
- 50Klbs to due east orbit LEO, not 65Klbs
- 3 weeks to launch from VAB rollout, not 24 hours

Traditionally, margin is used during the early stages of design as a contingency to allow for weight growth and growth resulting from addressing design and actual weight uncertainties (component and subsystem performance) during development and technology maturation. This type of margin should always be present in studies and preliminary designs with the amount of margin being dependent on the maturity of the subsystems, overall design and technologies. Also reference the section “Verifying Functional Requirements - Performance”. The unique nature of margin considerations is also clarified further in the section “Margin Considerations”.

Level: 1 - This type of margin, planned for a fielded operating system, should be included during concept evaluation and development as an early design requirement.

Visions of Improvement:

Basic improvement allocates extra margin early in the design at the overall program level, not within subsystems where it will be used as the traditional weight growth contingency. To the extent margin is then preserved or inherent in the fielded system it not only results in a more robust system but can be used for flexibility (higher payloads, different altitudes, different inclinations). This assumes a concept definition that intends to operate in a de-rated condition for all technical disciplines resulting in a very robust transportation system.

The current Shuttle has no system margin in the sense used here. For example, if it were decided to change a subsystem to improve the overall operability of the Shuttle and that change increased the Shuttle weight (a likely result), then other systems would also have to be modified to decrease their weight to make up the difference (difficult and expensive). Thrust would have to be somehow increased (either increasing cost or decreasing the life of the engines), or the payload capability on the nominal mission would have to be decreased. In other words, there is no system margin left in the fielded system.

Ideal levels of improvement would target robust systems designs which have more than adequate margin even after adjusting for uncertainties in development with expected weight growth.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be established. The amount of system margin over and above the weight growth and development uncertainty margins needed to achieve various levels of affordability and flexibility is not currently known. A target of 5 to 10 percent appears reasonable but would need to be quantified for each system since there is no previous history for this type of margin in space transportation systems.

(3) Number of systems with BIT / BITE (increase):

Shuttle Benchmark: Low - indeterminate as of this revision.

Derivation:

- This criteria is intended to include the health management of *fluid, mechanical and structural systems* as well as traditional electronics.
- The objective is to determine the overall health of the space transportation system to speed turnaround with as little manpower as possible.

The percentage of systems with built in test capability (Vehicle Health Management (VHM) or Health Management (HM) in general of flight and ground systems) or equipment relates very strongly to recurring costs such as operation of the system, and hence to life cycle cost and overall affordability. The correlation is also very strong to the ability to launch on time, launch on demand and the degree of supportability. Increases in the percentage of systems with BIT / BITE improves significantly in all these prior areas. This assumes the development of such systems is toward highly reliable sensors, software, hardware and computing capability.

Shuttle currently lacks true BIT / BITE for fluid, mechanical and structural systems and the use in electronic systems is limited in the ability to isolate problems to the lowest line replaceable unit (LRU) possible. Manpower intensive fault isolation of fluid systems such as propulsion contributes significantly to high turn-around times and low flight rates. Assuming reliability increases (addressed in other criteria) the criticality of space unique systems dictates that a significant requirement of future systems is improvement in fault isolation. For example, hazardous gas detection systems can indicate a leak in the ET intertank but can not specifically tell where.

Level: 3 - More detailed information that is available as the design matures to a preliminary design phase. However, all attempts should be made to determine this information as early in the decision making as possible especially in relation to evaluating one concept's merits against another.

Visions of Improvement:

Basic improvements include electronic systems with power on go/no-go capabilities taking maximum advantage of up to date computational capability.

Further improvements incorporate smart systems into fluid, mechanical and structural systems. This includes health indication capability for valves such as timing or sticking without recurring to unreliable microswitches or moving parts in general for sensing. Further improvement includes fast, low manpower leak isolation capability during turnaround such as for tankage. This means quickly being able to know if and where a leak is, not just that one exists in a general area.

More advanced improvement begins to provide built in, non-intrusive leak detection capability as part of health management for valves and critical propulsion systems. Eliminating physical connections or intrusions into the vehicle (such as flowmeters to test ports or accessing joints for mass spectrometry) is envisioned. All this while still being able to quickly assess as well as isolate any problems to the lowest LRU.

Maximum improvement provides a "brilliant system" for the entire space transportation system from landing to launch as well as in flight and orbit.

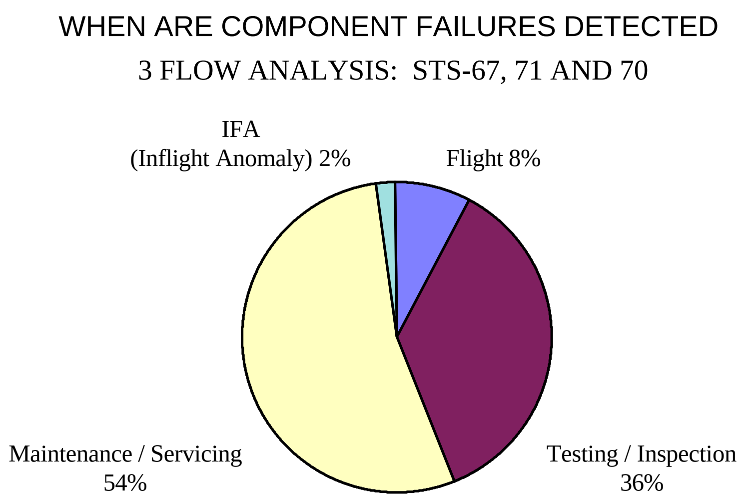


Figure B. The development of BIT / BITE capability for fluid, mechanical, structural and electronic systems would directly address the fault isolation which is 36% of when component failures are detected. Currently Shuttle relies on very manpower intensive approaches (non-BIT / BITE) for this part of turnaround activity. The 54% of fault isolation occurring during maintenance and servicing must also be addressed by means of BIT / BITE given it's manpower intensive non-BIT / BITE nature as well. Current remote health diagnostics emphasize the flight portion of the system. Source: Shuttle CAPSS / GPSS.

Target for Improvement:

This criteria is not a "pure" design feature a target for which can be easily established. It is included here as a critical *direction* for future systems to improve upon versus Shuttle. Two related issues are reliability and criticality.

- It is assumed reliability increases (another critical direction) result in BIT / BITE systems simplifying system turnarounds.
- It is assumed critical systems, regardless of robustness or reliability increases, will still require checkout, test or verification in some way and hence fault detection.

BIT / BITE must be targeted to these critical remaining areas (for example propulsion system leakage isolation) to avoid manpower intensive turnaround operations.

(4) Number of confined spaces on vehicles (reduce):

Shuttle Benchmark: 6 (majors only)

Derivation:

Confined spaces on a vehicle generally mean:

- Purges which mean ...
- Pneumatic systems and associated infrastructure (dedicated panels, supply facilities)
- Hazardous gas detection systems (HGDS) and associated infrastructure (dedicated panels and instrumentation)
- Potential hazards to personnel (O2 insufficiency)

This criteria includes compartments on the vehicle and associated interfaces that correlate very strongly to operation and support costs and hence to life cycle costs and overall affordability. The correlation is also very strong to simplicity and maintainability. Safety in particular is affected by this number for both the vehicle (explosive hazards) and personnel (lethal environments). The related infrastructure consists not only of the requisite high pressure pneumatic systems and facilities but also the associated hazardous gas detection capabilities. Criticality dictates high degrees of redundancy in the pneumatic systems further complicating the system and increasing both acquisition and operating costs. Hazardous gas detection capability, to the degree that precision and accuracy requirements exist, further adds to pneumatic system hardware and complexity to assure flowrate requirements.

Major Shuttle closed compartments include:

- ET/Orbiter interface at the 17-inch disconnects (purged and instrumented)
- External tank nose cone compartment (purged)
- ET to H2 vent arm ground umbilical cover plate (GUCP) (purged and instrumented)
- Orbiter to T-0 umbilicals (propellant servicing) (purged and instrumented)
- Orbiter aft boat-tail (purged and instrumented)
- External tank intertank (purged and instrumented)

Level: 3 - This criteria addresses more detailed information that is available as the design matures to a preliminary design phase. However, all attempts should be made to determine this information as early in the decision making as possible especially in relation to evaluating one concept's merits against another. Alternatively, a target or set of approaches that can possibly reduce this number should be maintained as a priority throughout concept development.

Visions of Improvement:

Basic improvements here are a challenge as SSTO type vehicles do not eliminate, but rather integrate tankage. Associated confined spaces may migrate as well. Aerodynamic considerations further exacerbate this number by precluding options (open trusses) that would have more easily applied to expendable vehicles. Access, also a criteria in this guide, is consistent with the goal of eliminating confined spaces and associated complexity if a third criteria, an increased number of components with demonstrated reliability, is properly addressed in development. This allows the selection of components for acquisition which have a reduced probability of requiring any access at all.

Basic improvements are possible at the interfaces for any SSTO compared to Shuttle. The use of an external, disposable tank with fuel and oxidizer disconnect cavities (confined, purged spaces) is eliminated by design.

Further improvements include precluding air intrusion into smaller compartments (such as a forward LOX tank nose cone compartment) such as through the use of foam or other material closeouts. This eliminates purge requirements.

More advanced improvement would eliminate interface compartments for servicing such as at a GUCP or T-0 umbilicals. Solutions such as an H2 vent line on board the vehicle routed to the servicing lines begin by eliminating separate systems.

Maximum improvement would target no aeroshell requiring a purge and instrumentation.

Ideal levels of improvement require maximum creativity to eliminate compartments currently accepted as requirements for access such as aft boat tails and propellant intertanks. This relates synergistically with the criteria “number of components with demonstrated high reliability (increase)”. The effect of up front development leading to high operational readiness and components with long life limits, high reliability and reusability, and robust margins is evident in the ability to dramatically improve, or not, on this confined spaces criteria.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be easily established. It is also a critical *direction* for future systems to improve upon versus Shuttle. A related issue to consider is criticality which dictates compartments with potential hazardous gas leakage should be purged and instrumented regardless of demonstrated reliability for the seals, protrusions and penetrations in that compartment.

(5) Number of hours for turnaround between launches (reduce):

Shuttle Benchmark: 3-4 months (per individual vehicle, serial time, not labor hours) between each launch, or 190,000 labor hours (direct labor hours only, orbiter OPF only), or use 4 to 10:1 ratios for the sum of direct and indirect labor hours (orbiter OPF only, launch site only, actual expenditures higher).

Derivation:

This criteria correlates strongly to recurring costs, such as operation of the system, and hence to life cycle cost and overall affordability. The ability to launch on time, the ability to meet planned requirements (capacity) such as time and number of launches, and the overall supportability of the system all relate to this criteria.

For Shuttle this measure in serial time is measured in months. In manhours the measure is in hundreds of thousands of manhours if counting *only* direct labor charges.

Level: 3 - Reference "Target for Improvement".

Visions of Improvement:

Days not weeks. Hours not days.

Target for Improvement:

This criteria is not a "pure" design feature. It is included here as a critical *direction* for future systems to improve upon versus Shuttle. A reduced number of hours for turnaround is a <u>resultant of design features</u> that are included in this guide.

The high rank (4) for this criteria is an indication of the importance of understanding the recurring work associated with a design, such as for turnaround of one vehicle. This is a key question in decision making including technologies to develop, which to acquire or implement, and how to integrate them into a system as well as the final risk that flight and cost rates will be achieved or not. Targeting should aim for zero turnaround operations other than servicing of propellant and expendables as a general ground rule for starting a design exercise.

The high rank also stresses the need for adequate models of vehicle or fleet operations based on an understanding of the implications to operations of certain designs and development and acquisition strategies. The other design features and program features in this document provide a sense of direction using significant criteria that can aid in understanding future turnaround scenarios.

MISSION	UNPLANNED		PLANNED		ORBITER MODS		TOTAL OPF
	MHRs	%	MHRs	%	MHRs	%	MHRs
STS-31R	23606	14.49	132169	81.13	7130	4.38	162905
STS-41	55887	20.64	205340	75.83	9559	3.53	270786
STS-38	27470	15.45	147204	82.77	3175	1.79	177849
STS-35	39175	21.35	139903	76.23	4441	2.42	183519
STS-37	19271	10.46	160689	87.22	4284	2.33	184244
STS-39	50174	20.83	184276	76.52	6367	2.64	240817
STS-40	41391	20.42	153623	75.79	7677	3.79	202691
STS-48	23512	16.53	113537	79.81	5211	3.66	142260
STS-42	18609	13.18	120129	85.11	2402	1.70	141140
STS-43	19830	15.62	105107	82.78	2032	1.60	126969
STS-44	22781	16.33	114018	81.75	2675	1.92	139474
STS-45	11517	11.07	89466	85.99	3063	2.94	104046
STS-49	82139	21.74	281609	74.52	14145	3.74	377893
AVERAGE	33489	17	149775	80	5551	3	188815

Table 2. Turnaround times between launches are dictated by both planned work and unplanned work. This data for Shuttle orbiter turnaround manpower requirements does not include the integration activities in the VAB, involving mating the orbiter to the External Tank (ET) and Solid Rocket Boosters (SRB's). This adds another 7 days on average to turnaround time. It also does not include time on the pad, on average another 30 days to add to turnaround time. Source: Shuttle CAPSS.

(6) Number of different propulsion systems (reduce):

Shuttle Benchmark: 4 *plus*

Derivation:

This criteria relates very strongly to recurring costs, such as operation of the system, and hence to life cycle cost and overall affordability. The correlation is also very strong to the ease of integration and the degree of supportability. The associated separate infrastructures, organizations and manpower result in the high rank for this criteria.

The Shuttle uses 4 completely independent propulsion systems:

- LOX/LH2 main engines (3)
- Solid Rocket Boosters (2)
- Orbital Maneuvering System using hypergols (2 Pods plus aft RCS)
- Forward Reaction Control System (RCS) using hypergols

Level: 1 - Usually available early in the concept development and evaluation.

Visions of Improvement:

Basic improvements would be achieved in any SSTO concept over Shuttle by virtue of deletion of the SRB's. Launch assist concepts would not change this number assuming a Shuttle type configuration (MPS, Sled, and separate OMS and RCS = 4).

Further improvement would combine more of the hardware for both main propulsion as well as orbital maneuvering. Turbopump operating ranges would likely require expansion. Common thrusters and or nozzles would be consistent with this moderate level of improvement.

Further improvement would synergistically combine this criteria with top ranked criteria such as reducing the number of different fluids or reducing the number of toxic fluids. A combination OMS/MPS with a separate RCS but all using common fluids would be an improvement.

Maximum improvement would continue to build on all of the prior by adding further degrees of common hardware (such as tankage) for all propulsive functions (MPS/OMS/RCS). The number of different propulsion systems would then have reached a comparison value of between 1 and 2 (some common hardware).

Target for Improvement:

This criteria is a “pure” design feature a target for which can be set with relative ease. Improvement may be measured relative to the 4 independent Shuttle systems.

(7) Number of unique stages, flight and ground (reduce):

Shuttle Benchmark: 3

Derivation:

The Shuttle stages include solid rocket boosters, external tank and orbiter. The number of stages used in a space transportation system relates very strongly to recurring costs, such as operation of the system, and hence to life cycle cost and overall affordability. The correlation is also very strong to ease of integration and the degree of supportability. Reductions in the number of stages improves significantly in all these prior areas.

The relation of major interfaces to costs, both recurring (operational) and non-recurring (acquisition), makes this a significant feature of a design.

Level: 1 - Usually available early in concept development.

Visions of Improvement:

Basic improvements would be toward a single stage to orbit vehicle.

A ground assist concept, such as with a sled propelled by some means, would count as two stages (negative impact on this criteria). A flight second stage would have an equal number (two) as a sled concept; however, other criteria would be affected differently according to the particular traits of the sled or flight stage. For two stages versus single stage operations the increased one time facility costs and increased annual operations costs resulting from two stages can significantly affect life cycle costs (Hamaker 1996)[11].

Target for Improvement:

This criteria is a "pure" design feature a target for which can be established with relative ease. A particular two stage design is not excluded over a single stage design. Consideration of the whole set of design features, and especially the significant first 20 to 29, should be weighed in determining if a particular set of design variables is an improvement over another. Within the intent of this guide no one criteria is a means for decision making; rather, the extent to which an architecture optimizes on most of the top features can be an indicator of connecting to higher level goals such as routine, affordable space transportation.

(8) Number of active ground systems required for servicing (reduce):

Shuttle Benchmark: Numerous. Exact value unknown as of this revision.

Derivation:

- Active ground systems required for servicing include not just propellants but other fluids or expendables.

- Shuttle active ground systems required for servicing include:
    - LO2/GO2 and LH2/GH2 propellants storage and handling
    - GHe and GN2 facility systems
    - Fuel cells power reactants (LO2/LH2)
    - Hypergolics OMS/RCS (N204 and MMH)
    - Hypergolics APU's (Hydrazine)
    - Hydraulic systems
    - Environmental Control and Life Support Systems (ECLSS)
        - Freons
        - Ammonia
        - Water

The number of active ground systems required for servicing relates strongly to the affordability of operations and support, the capacity of the system (ability to meet multiple customers planned requirements such as time, payload size, and weight, number of launches, launch rate and payload destination), the ease of vehicle and system integration, maintainability, the ability to launch on demand and supportability.

Level: 2 - Information is available on this criteria as the concept becomes more defined. However, this should be considered critical information required of any concept very early in decision making.

Visions of Improvement:

Basic improvement here begins with a common propellants ground rule (NASA SGOES 1988)[18]. Servicing can then be integrated and ground infrastructure simplified and reduced. Vehicle systems can also benefit from greater integration. Examples include propellant grade fuel cells and O2/H2 based auxiliary propulsion. Power supplies using non toxics would begin to simplify servicing by eliminating bulky, hazardous scape operations. Power supplies providing both on orbit requirements as well as high horsepower ascent or landing requirements (TVC, aerosurfaces, landing gear) would simplify vehicle systems servicing by eliminating separate systems servicing.

Further improvement would address ECLSS and thermal management requirements. Eliminating any need to violate system integrity would begin to enable closed loop systems not requiring servicing during turnaround. For example, hydraulic systems with the capability of actuating, such as for checkout, without ground interfaces violating system integrity are desirable.

More advanced improvement would make any remaining servicing requirements low on manpower requirements such as through automated or simplified umbilicals with rapid integrity checkout capability.

GROUND SYSTEMS LRU PR'S BY FLOW

FROM 1/89 TO 5/94

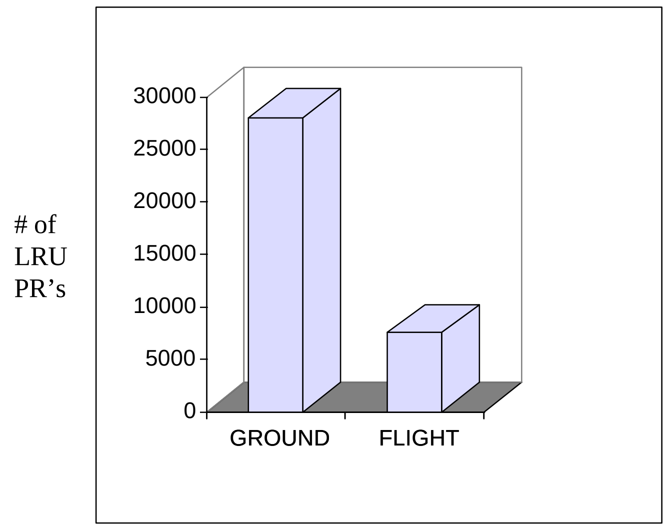


Figure C. The "LRU PR's" (components actually removed and replaced) for the Shuttle ground systems per flow are about 800 on average. Active ground systems account for a significant portion of this turnover. Source: Shuttle PRACA system.

Target for Improvement:

This criteria is a "pure" design feature which represents actual hardware that can be accounted for. Improvement may be measured relative to complex Shuttle systems.

For example, a design may target one servicing operation - propellant loading, although multiple liquids, gases or charging of electronic (power) systems may be involved. Serial operations or servicing and intrusive breakage of one system to support the checkout of another should be avoided. Serial operations as a schedule risk reduction may be indicative of unreliable hardware with potential hazards which relates to other criteria that must be improved upon in future systems (for example "number of components with demonstrated high reliability").

(9) Number of purges required (reduce):

Shuttle Benchmark: Numerous. Exact value unknown as of this revision.

Derivation:

The Shuttle system requires numerous purges for (1) closed compartment inerting (reduce O2), conditioning (humidity) and temperature control as well as (2) ice prevention external to the hardware and (3) protecting hardware from the elements (salt spray, SRB dust, corrosion).

Also reference “Number of closed compartments”.

Major purges on Shuttle include:

- ET/Orbiter interface at the 17-inch disconnects (purged and instrumented)
- SRB aft skirt GN2 purge
- GO2/GH2 Pressline purge
- LH2 vent shroud
- External tank nose cone purge
- ET to H2 vent arm ground umbilical cover plate (GUCP) (purged and instrumented)
- Orbiter to T-0 umbilicals (propellant servicing) (purged and instrumented)
- Orbiter aft boat-tail (purged and instrumented)
- External tank intertank (purged and instrumented)
- Assorted valve stem purges
- TSM purge
- Pneumatic panels (enclosure / boxes) purged

Level: 2 and 3 - This information is usually not expected in early concept definition. The information becomes available as the concept matures and goes toward a preliminary design phase.

Visions of Improvement:

Basic improvement is achieved as a concept reduces stages such as an SSTO. Element interfaces and boosters are deleted.

For improvement beyond the prior a vehicle thermal protection system would be required to be more robust so as to withstand ice impacts should any form during loading. This is a driver of the GO2/GH2 pressline purge and the H2 vent shroud purge.

Further improvement would build on the prior and eliminate interface purges as well such as for umbilicals.

Maximum improvement would delete the need for purges in major vehicle compartments such as in engine aft compartments or intertank areas. The relation of these is to costly infrastructure which is both critical to being able to launch on time as well as to safety. This in turn addresses purges for compartments such as ground infrastructure pneumatic panels. The purge is desirable in pneumatic panels since enclosures protect against the environment; however, the elimination of functions reduces the baseline number of these panels.

Target for Improvement:

This criteria is a “pure” design feature a target for which can established based on the following questions: (1) is the thermal protection system targeted to be robust enough to withstand ice impact with zero damage, (2) are interfaces for loading or venting targeted to have closed compartments or not and (3) how much ground infrastructure such as for gas supplies or valve actuation are targeted (how many pneumatic systems?).

This criteria is extremely synergistic with the “number of potential leakage sources” and the “number of closed compartments”. Improvements here generally improve in these other areas as well.

See “number of potential leakage / connection sources (reduce)”.

(10) Number of components with demonstrated high reliability (increase):

Shuttle Benchmark: Low - Indeterminate as of this revision.

Derivation:

Mature technology is a cornerstone of reliable operations. Up front development of systems to a high operational readiness reduces the risk later that vehicle productivity goals will be met. A design for support results. This criteria correlates strongly to initial acquisition costs, to the affordability of eventual operations and support, to the reliability of systems during turnaround and to the safety and mission reliability of the design.

- The term "reliability" as used here is comprehensive in scope. It includes reliability during turnaround (process reliability) as well as in flight operations. The link between (1) mission reliability, (2) the means by which this reliability is achieved ("designed in" *or* "inspected, tested, repaired and replaced in") and (3) the affordability of operating a system requires this broad view of the term.

Level: 3 - More detailed information that is available as the design matures to a preliminary design phase. Particularly as the certification practices, reusability, reliability and maintainability goals and approaches are defined. Final definition is not obtained until actual qualification tests, design iterations and further demonstrations of life limits and analysis are complete.

Visions of Improvement:

Basic improvements in this criteria begin with an understanding of data, such as from Shuttle, to adequately understand the reliability of designs. These measures include but are not limited to:

- Mean Time Between Failure (MTBF)
- Mean Time to Repair (MTTR)
- Logistics Down Time (LDT)
- Availability, total system as well as subsystems (Ai)
- Life limits (both maximum/minimum on/off cycles as well as usage time). This encompasses low cycle fatigue problems as well as high cycle fatigue.

Basic implementation then takes these baseline data (such as for Shuttle) and targets new goals. A basic improvement would be the implementation of a development and qualification program framed to achieve these goals for evolved hardware. Further improvement builds on the prior through actual, extended flight history and the compilation of data that allows further iteration as systems are upgraded individually.

Maximum improvement envisions low cycle time between product developments that quickly build on previous product experience. One reusable launch system builds on another in quick succession. Improved computational techniques allow testing and design changes to be done quickly and at minimal cost versus test stands and tests to failure of actual hardware.

The high rank for this criteria stresses the need for rigorous test of designs pre-acquisition in the qualification / certification phase so as to have supportable, fast turnaround systems. This criteria is extremely synergistic with the pre-operational program considerations contained in this guide.

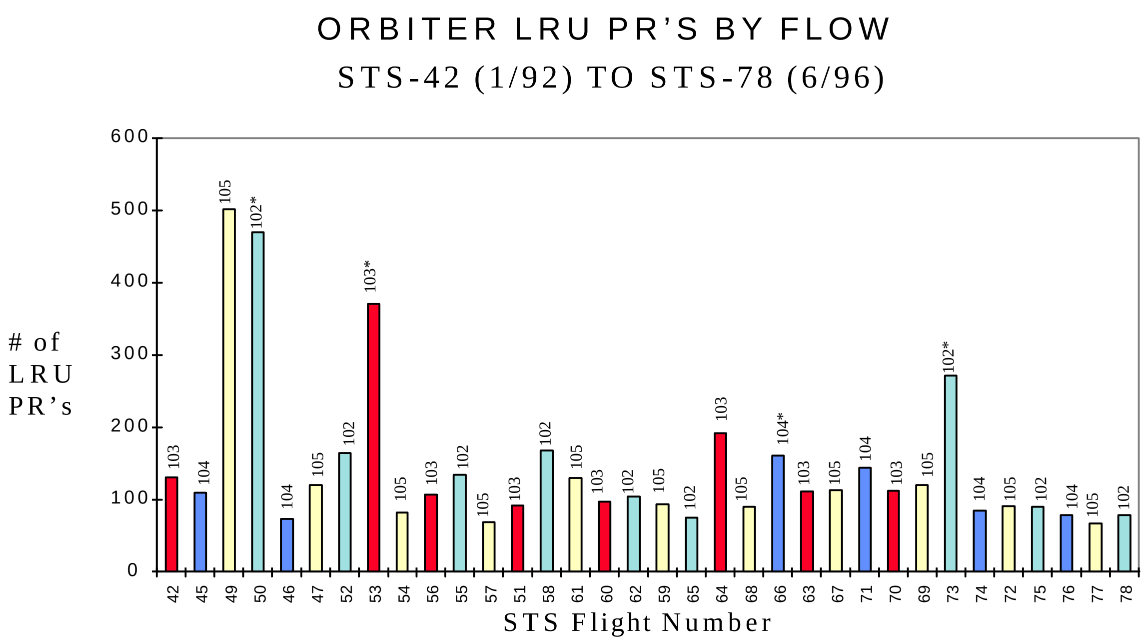


Figure D. The "LRU PR's" (components actually removed and replaced) for one orbiter per flow are over 100 on average. The chart does not include SSME or tile. Post OMDP (marked with an ""), the LRU counts at KSC are notably above average. The chart includes only work done in the OPF. Ground systems would add over 700 more LRU PR's on average per flow. The STS-49 flight was OV-105's first. Source: Shuttle PRACA system.*

- **Certification and Life Cycles**

The development of long life limits has a major effect on the certification of future transportation systems. At one extreme, aircraft certification is done once and maintenance results in "maintaining certification" of an aircraft. At another extreme, Shuttle certification (a CoFR) is done every flight and processing, including maintenance, test, checkout and repair is the means of achieving *certification each and every flight*. High cycle life is key to true reusability, reducing failures, increasing the time between scheduled maintenance and reducing operating costs and hence greatly reducing life cycle costs of a transportation system.

Target for Improvement:

This criteria is not a “pure” design feature even though targets for subsystems may be established analytically. Reliability, Maintainability and Supportability (RM&S) studies can gather data and set targets; however, the <u>*implementation*</u> of a program to achieve these targets - the testing, design iteration, analysis, and demonstration of designs - is not as easily defined as for other criteria. Programmatic considerations are synergistic with this criteria. Up front decisions such as which technologies to fund, which to focus on extending life limits for, and which to iterate (improve on) more in the design and technology cycle, are the programmatics that will determine the degree to which this criteria is high or low on any system eventually acquired.

This criteria is included here as a critical *direction* for future systems to improve upon versus Shuttle. Shuttle may be considered the implementation of a system with low levels of demonstrated reliability, in particular process reliability, the reliability of components during turnaround. Improvement may be measured relative to the degree to which components, sub-systems and eventually whole systems measure in demonstration compared to similar existing Shuttle systems or approaches.

(11) Number of potential leakage / connection sources (reduce):

Shuttle Benchmark: Fluids ≈ 10^3-10^4, Electrical ≈ 10^4 - 10^5 ROM. Precise value indeterminate as of this revision.

Derivation:

This includes electrical and fluid systems.

For fluid systems, manpower intensive operations are driven in Shuttle processing by a combination of (1) high numbers of potential leakage sources for fluid systems, (2) the use of manual methods in fluid systems certification (hands on including over a dozen approaches), (3) the criticality of systems dictating high numbers of required tests and (4) the lack of reliability of components further dictating high numbers of required tests for seals as well as components removed and replaced.

Electronic systems (all vehicle systems) require a separate computerized database ("SCAN") for tracking all connectors that are disassembled, reassembled and retested (> 5000+ pins on average requiring recertification per turnaround with an increase in this number by one order of magnitude to > 30,000 pins for the flow following depot maintenance). Unfortunately, a similar computerized, central database does not exist for fluid systems and the degree of de-configuration and retest for fluids is unknown to any high certainty.

The number as a baseline can be considered in either of two ways. First, potential sources, even if no requirements exist for verifying integrity (unless broken into) and second, required verifications. Required fluid verifications are estimated in the order of thousands of leak checks per Shuttle flow.

Some examples:

- LOX Facilities: >1000 per flow (leak checks)
- LH2 Facilities: >1000 per flow (leak checks)
- ET Processing: > 20 per flow, much higher if hazardous gas detection requirements during loading are included.
- MPS Processing: > 40 per flow + >30 interfaces
- Shuttle Main Engines: >80 per flow per engine + >10 interfaces

To clarify, the prior in systems such as facilities, are driven by infrastructure such as pneumatic panels. A requirement for a nosecone purge brings with it a pneumatic panel, heater and controllers. Also, the prior <u>does not include bulk leak checks</u> done using hazardous gas detection capabilities scanning whole engine blocks, ET intertanks or aft compartments. This would increase the count into the tens of thousands of joints. These integrated or functional fluid system verifications are no less manpower intensive than individual joint tests given the need for sophisticated equipment, purges, firing room monitoring and GSE setups - most manual.

Other systems such as freon cooling loops (ECLSS) using high degrees of brazing do not have periodic, individual leak checks. However, systems which only check violated joints are not immune from numerous verifications given high component failure rates such as thrusters for OMS/RCS or required breakage into systems as part of processing such as for hydraulic systems.

Level: 3 - More detailed information that is available as the design matures to a preliminary design phase.

Visions of Improvement:

There are various levels of cumulative improvement possible for this criteria.

- Systems deletion / systems simplification
- Systems reliability - seals and sealing techniques
- Systems reliability - components (Also reference other criteria such as "number of components with demonstrated high reliability")
- System robustness to leakage (design tolerance to wider variation in operating parameters)

Basic improvements begin with the simplification of systems. SSTO concepts by definition reduce potential leakage and connection sources by eliminating the integration of distinct stages or segments. Cabling in SRB segments as well as fluid and electrical interfaces to disposable tanks or SRB's are deleted. Further basic improvements would simplify major fluid systems such as propulsion, eliminating purges and associated ground infrastructure. The elimination of GHe inject systems, POGO systems and turbopump interseal purges further provide basic levels of improvement.

Sled launch assists could entail similar interfaces for fluid and electrical systems negating a portion of the interface gains mentioned previously. Further, the introduction of more cryogenics such as liquid helium (LHe) for superconducting applications introduces potential leakage sources. This area is synergistic with "number of (%) of propulsion system automated (increase)". The automation of interface checkouts such as leak checks would address the manpower factor associated with leakage and connection points.

More significant improvement, assuming complex fluid systems will continue to be associated with propulsion systems and servicing requirements, would entail seals and sealing techniques dramatically improved over current designs. Welding, brazing or otherwise eliminating leak paths would eliminate the associated tasks and manpower. This assumes much higher levels of component reliability as well as ease of manufacture. It also assumes areas are not regularly accessed reducing the probability of unintended personnel damage.

Maximum improvement builds on the prior (deletion, automation and new seal techniques) and adds increased component reliability. This precludes work in areas that are susceptible to damage. For example, a new welding technique that is easy to use in manufacturing and to verify and which eliminates periodic maintenance checks may not be implemented due to high probabilities that intensive component refurbishment in the area causes unintended damage to lines. This applies also to connectors and cabling and electronic components. Notice the synergy here to “number of components with demonstrated reliability (increase)”.

Finally, ideal synergy would take one more step. The “number of potential leakage / connection sources (reduce)” is synergistic with a high number of the other criteria contained in these guidelines. Assume advances in the area of “number of confined spaces on vehicles (reduce)”, which in turn allow improvement in the criteria “number of purges required (reduce)”, thus improving on the “number of active systems to maintain a safe vehicle (reduce)”. The prior assumptions would greatly benefit through simplification the “number of potential leakage / connection sources (reduce)”; however, a major component of launch system infrastructure and cost would have gone without addressing - pneumatic systems for valve actuation.

To complete building on the ideal target for improvement, the introduction of electronic systems would be a highly promising approach. Tank vent valves, as well as all vehicle valves and facility valves could be motor driven (electromechanical valves). This adds electrical connectors but drastically reduces fluid systems leakage sources and massively eliminates infrastructure (GHe/LHe and GN2/LN2 facilities, truck farms and tube banks). Electrical connectors can also more easily include self test capabilities. These electrical systems in turn would allow further improvement in areas of health management and automation (such as “number of systems with BIT / BITE (increase)”. Compatibility and electrical concerns for areas such as LOX could be addressed through design and materials selection as well as zero seal magnetic couplings.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be established with relative ease as a design matures. It is also a *direction* for future systems to improve upon versus Shuttle. Basic reductions inherent to an SSTO or even a sled assisted concept do not represent the limits of possible improvement.

The high rank here stresses the need to target seals and sealing techniques as requiring much improvement in any next generation concept. Improvement must also target component reliabilities to have maximum effect. Pneumatic systems should be targets for virtual total replacement with electronic systems of valves on the vehicle and the ground.

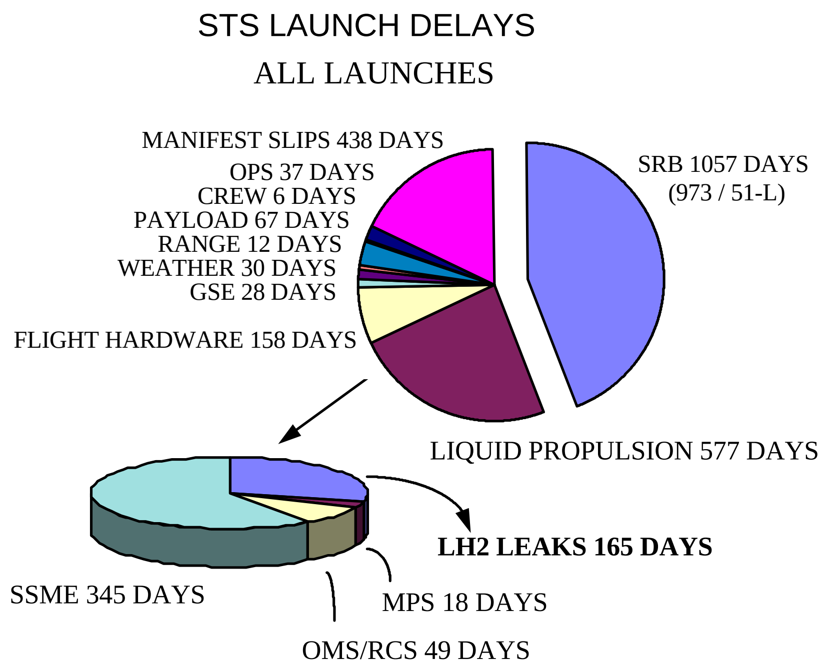


Figure E. Liquid propulsion systems on Shuttle have dominated launch delays. The LH2 leak days of delay are primarily contributed by the STS-35 and 37 flows in 1990. Note that the SRB delay contribution is mostly 51-L. Leaks constitute not only a launch on time issue but a recurring aspect of manpower intensive operations targeted at preventing such incidents. Recurring operations, such as leak checks in fluids systems, are directly linked to the reliability as well as criticality of systems. To support recurring verifications of system integrity multitudes of leak check methods are in use as shown. Source: LSOC Database

LEAK CHECK METHODS	ORB HYD	SRB HYD	ORB APU	SRB APU	SSME	MPS	ET	PRSD FC	HGDS	OMS	RCS	ECLSS	CRYO FAC
VISUAL													
Bubble soap			X	X	X	X	X	X	X	X	X	X	X
Presence of liquid wetting / drops	X	X		X	X	X		X				X	
Inflated baggy					X								
Submerged H2O bath													
Submerged sense line in H2O bath													
AUDIBLE					X								X
FLOWMETER			X		X	X	X	X	X			X	X
MASS SPECTROMETER													
GHe only			X		X	X		X		X	X	X	
Multiple Gas Analyzer (MGA)					X								
HGDS					X	X							X
PVT	X	X	X	X		X		X		X	X	X	X
SYSTEM PERFORMANCE								X					
FLUID QUANTITY VERIFICATION						X		X				X	
LEAKAGE CAPTURE / DISPLACE H20				X				X					
USON PROBE GAS DETECTOR (GHE)													X
TOXIC VAPOR DETECTOR										X	X		
HALOGEN LEAK DETECTOR												X	

(12) Number of active systems to maintain a safe vehicle (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

This includes ground supplied purges, hazardous gas detection capability during loading, turbopump interseal purges, GHe inject during loading, LOX bleeds during loading, hydraulic heating in orbit, replenish valves during loading, flow control valves during ascent and a host of other systems.

This criteria has a strong synergistic relation with the “number of purges” as well.

Level: 2 - Information is available on this criteria as the concept becomes more defined.

Visions of Improvement:

Basic improvements begin with the deletion of the root causes requiring these active systems for safe operation. This results in simplification of systems. Shorter feedlines such as with a LOX tank aft must trade the elimination of active systems such as GHe inject against any flight concerns and active systems for stability of flight. Flow control valves for in flight cryogenic tank pressurization can be replaced with fixed orifice designs if system design goals target robust tanks and structural margins. Reduced margins in cryogenic tank structures that require higher pressure settings during loading are undesirable. Vent valve cycles, an active system, increase and work against this criteria.

Further improvement would indicate active cooling systems for thermal protection, such as with an airbreather at high Mach numbers, is undesirable. The criteria “number of potential leakage and connection sources” is also synergistically, adversely affected by active cooling. Benefits (reference criteria “26 - Average Isp on reference trajectory”) of higher Mach number approaches requiring active cooling must be weighed against these related negative acquisition and operation aspects.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be established based on an active accounting of current systems such as Shuttle. A further determination of which systems may be deleted and which, for a new system, are essential would also indicate the *direction* in which a new system is heading. The high rank for this criteria stresses the importance of improvement in this direction.

(13) Percent (%) of propulsion system automated (increase):

Shuttle Benchmark: ≈ 0

Derivation:

- Reference is to <u>turnaround</u>, not flight.

This criteria is a subset of the criteria "number of systems with BIT / BITE (increase)".

This criteria is synergistic with the criteria "average Isp on the reference trajectory (increase)".

This criteria is re-addressed here specifically for propulsion given that propulsion alone has a very strong correlation to the sensitivity to flight growth costs, operation and support, the capacity of the system, the maintainability of the system and even safety concerns. Being able to increase flight rates (vehicle utilization) without increasing overall costs results in a desirable sensitivity to costs per flight, in a decreasing direction. Expenditures in automation up front in development and acquisition relates to this ability to produce high flight rates per vehicle.

Assumptions again include reliable, non-intrusive instrumentation. The reliability assumption is synergistic with the criteria "number of components with demonstrated reliability" and to development and certification activity. The non-intrusive assumption is synergistic with the "number of potential leakage / connection sources".

Currently, Shuttle has little of the previous characteristics. Manpower intensive (manual) operations are the norm for the propulsion systems turnaround (main propulsion, external tank, servicing facilities and interfaces, orbital maneuvering systems and reaction control systems). "Manual" describes assorted tasks. For example, (1) having to individually perform mass spectrometer leak checks (passing detectors slowly over and around individual joints and having to bag these in some cases) or (2) having to install access kits to break into joints, install plugs, and configure and connect flow meters and K-bottles for one leak check and (3) having to do this repeatedly for multitudes of joints and (4) having to remove access kits followed by meticulous inspections of areas to be "closed out". Bulk leak checks (many joints at one time) using hazardous gas detection capabilities and "cans" or the existing compartments (such as the aft) result in knowledge of leaks existing or not but not necessarily of where or which one of the many joints. This causes the previous manual operations to go into effect.

Level: 2 and 3 - This information is usually not available early in concept definition. The importance in early decision making and eventual results exists nonetheless.

Visions of Improvement:

Reference "number of systems with BIT / BITE (increase)".

A list of propulsion operations in broad categories would be:

- Leak checks
- Valve checkout (including check valves and relief valves)
- Electrical systems checkout (cabling, controllers, interfaces)
- Hydraulic systems checkout
- Servicing interfaces checkout
- Engine checkout (inspections of turbopumps, purges, drying)

Basic targets for improvement would delete hydraulics (synergistic with "number of toxic fluids (reduce)" and with "number of potential leakage / connection sources (reduce)"). Basic improvement would also extend life limits on engine components by addressing low cycle fatigue transients and duration or high cycle fatigue wear. These would be addressed in startup sequencing development as well as new technology. This would in turn begin to preclude the removal of engines from flight to flight, hence reducing interface checkouts such as inspections, connections and leak checks. The full benefits of automating turnaround checkout can then begin to be exploited. For example, low cycle fatigue life in turbopumps can be improved by controlling start transients to minimize or eliminate those mixture ratio variations during the transient that cause rates of temperature change such that the core and the surface of the blades and nozzles can not track each other and thus produce significant temperature differences and resulting thermal strains; and by controlling the shutdown to reduce or eliminate the same problem during the quench. High cycle fatigue can be addressed by instrumentation and internal flow passage designs to minimize flow induced vibration.

The synergy of turnaround automation with component reliability must be stressed.

For those fluid areas remaining, such as interfaces for servicing umbilicals, the automation of connection, checkout including leak checks, and servicing would be a further improvement.

Eventual targets should include the prior and the transition to electronic systems for broad application to valves and on board instruments that are non-intrusive. Reference "number of potential leakage / connection sources (reduce)".

One point to account for in sled launch assist concepts, which would be part of the propulsion system, is all electrical systems versus systems using a cryogenic commodity such as LHe (for superconductors such as in some maglev concepts). Cryogenic commodities in addition to those in use today would work against the direction of improvement for “number of potential leakage / connection sources” and would add another system that would require (1) intensive manpower similar to current cryogenic propulsion systems or (2) add to the list of automation that this criteria stresses is required in future propulsion systems. Improvements in automation of servicing umbilicals could just as easily apply to a sled with LHe requirements as to the actual vehicle interfaces.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be established based on the total number of planned tasks and how many of these tasks will be done via automation for any given concept. It is also a *direction* for further improvement.

(14) Number of hands on activities required (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

Reference “5-number of hours for turnaround between launches (reduce)”.

This criteria correlates strongly to recurring costs, such as operation of the system, and hence to life cycle cost and overall affordability. The ability to launch on time as well as meeting planned requirements all relate to this criteria.

Level: 3 - Reference “Target for Improvement”. Information for a concept relating to task requirements and the nature of these tasks, manpower intensive or not, may not be available early in concept development or decision making. An evaluation of features that are more easily measurable (number of toxic fluids, number of stages, number of propulsion systems) as well as the intended direction of development (number of systems with BIT/BITE, number of confined spaces, number of components with demonstrated reliability, number of leakage / connection sources), can indirectly give a sense of positive or negative improvement in this criteria.

Visions of Improvement:

Basic improvements would include interfaces (any number of stages or ground support tasks) that are automatic to a degree that manpower is counted in the dozens, not hundreds of “touch labor” personnel.

Further improvements assume concepts that land, are connected to immediately, and only require refueling or servicing of expendables, to launch again.

Target for Improvement:

This criteria is not a “pure” design feature a target for which can be easily set. It is included here as a critical *direction* for future systems to improve upon versus Shuttle. A reduced number of hands on activities is a <u>resultant of design features</u>, pure and directional, that are included in this guide.

Tasks that exist for Shuttle are for the most part “hands on”. Launch control center remote activity is not “hands on” by definition but is usually coupled to personnel in the field. As an example, securing a launch pad following launch requires over 100 personnel in the immediate hours after launch at that pad with about equal numbers of personnel at remote sites such as the launch control center.

The high rank of this criteria stresses the need to adequately understand the hands on activities associated with certain designs. A model of vehicle processing and turnaround with associated manpower is a parameter as important in a concept definition as a performance model that verifies the thermodynamic closure of an engine cycle.

MISSION	TOTAL OPF LABOR HRs	TOTAL TPS LABOR HRs
STS-31R	162905	78471
STS-41	270786	146719
STS-38	177849	84545
STS-35	183519	80155
STS-37	184244	92187
STS-39	240817	91184
STS-40	202691	97213
STS-48	142260	65309
STS-42	141140	80880
STS-43	126969	59575
STS-44	139474	60416
STS-45	104046	45863
STS-49	377893	52744
AVERAGE	188815	79635

Table 3. Thermal Protection Systems, in the Shuttle case due to lack of robustness and a need for waterproofing, are one principal component of hands on activity. Laborhours on TPS account for 1/3 to 1/2 of all OPF laborhours. Performance requirements combined with previous technology limitations dictated this. New technologies and approaches must address not only performance requirements as a given but also the need for robust, zero-maintenance thermal protection systems. Source: Shuttle CAPSS. TPS hours include backshop. Total OPF hours shown include TPS hours.

Access to Space Report [14], Budget Baseline 1994, Shuttle Thermal Protection System Operations, Logistics, KSC Thermal Protection System Operations, KSC	Labor, Head Count 153 250
Waterproofing Operations, Shuttle (NASA Ames, 1994)[15]	Labor, Hours per Flow 2,268

Table. 3a The example given here for Thermal Protection Systems, as with any hands on activity, should not obscure the larger component of indirect costs that associate with any activity directly tied to a space transportation system. For example, head count for facility operations and maintenance at KSC (Access to Space, 1994)[14] is 1,298; for the on-going production of expendable elements, external tanks at Michoud, LA, it is 2,376.

One particular area that must be a major target for future improvement in the area of hands on activity is thermal protection systems. The manpower intensive nature of Shuttle TPS is shown in Table 3 and 3a. Robustness improvement here is very synergistic with other criteria such as the need for purges (criteria 9) or active systems (criteria 8) that prevent ice formation external on the vehicle (Shuttle pressline, GH2 vent shroud, GOX vent arm and associated purges), toxic fluids (criteria 1) such as waterproofing agent and turnaround time (criteria 5).

Note that the increased use of an active vehicle thermal protection system (active cooling via fluids) for aerosurfaces, forebody, leading edges, or propulsion works against 2 major criteria, criteria 11 on potential leakage sources and criteria 15 on active components required to function. The same applies to active thermal management systems such as for avionics or environmental control. These in turn are direct relationships to hands on activities. Improvements reducing hands on activities for any reusable vehicle must target this major component, the thermal protection system, while providing solutions linked to the other criteria as prioritized.

(15) Number of active components required to function including flight operations (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

Reference “number of active systems to maintain a safe vehicle”.

This criteria emphasizes function versus safety. Shuttle requires systems such as recirculation pumps for conditioning during loading or ground pumps for supplying LOX. Dependability, the ability of hardware to perform when needed the first time, every time, strongly correlates to this criteria. The probability of intact vehicle recovery and mission success correlate to this criteria. Simplicity, or if active systems are numerous, complexity, also correlates strongly to this criteria.

Explosive charges for separating interfaces are an example of active systems that must function and are dependable, yet are not supportable. They are manpower intensive as well as safety concerns and operations impacts (causing clears.)

Thermal management using fluid systems in active cooling loops (for avionics, personnel, fuel cells, hydraulics) are another example of active systems on Shuttle.

Level: 2 and 3 - Information on this criteria is usually not available early in concept development. As the design matures this information can be used to assess the likely supportability of a concept.

Visions of Improvement:

Basic improvements would target rotating machinery such as ground pumps or on board recirculation pumps. Further improvements would include passive thermal management schemes for electronics as well as any other heat generating devices. Low voltage electronics and forced convective cooling (fans) could simplify systems overall.

For future systems possible additions and hence negative impacts include active cooling during ascent, retractable engine fans and variable geometry requiring active closure, opening or variation of flow paths. These would also impact negatively criteria such as “number of potential leakage / connection sources”.

Maximum improvement would reduce Shuttle type systems while avoiding a net increase due to the addition of entirely new functions to be achieved.

Target for Improvement:

This criteria is a “pure” design feature a target for which can be established based on an active accounting of current systems such as Shuttle. A challenge is also accounting for potentially new active systems in future concepts such as active cooling during ascent, active engine components such as retractable fans, variable geometry requiring active closure, opening or variation of flow paths and turbomachinery count (or the “number of engines”).

It is also included here as a *direction* for future systems to improve upon versus Shuttle if qualitative improvements such as dramatically higher affordability and individual vehicle flight rates are a goal.

(16) Technology Readiness Level (TRL) (increase):

Shuttle Benchmark: Low - indeterminate as of this revision.

Derivation:

Technology Readiness Levels (TRL) as defined by NASA require reassessment focused on applications, operational costs and demonstration in valid environments. Shuttle represents technology implementation with low TRL ratings *if* an understanding of operational implications is considered a part of the TRL definition. By functional definition the TRL ratings are high. Operability assessments of technologies are required if TRL rankings are to be used to focus on the recurring costs aspects of technologies.

Level: 1 or 2 - These values may be determined early in concept development and demonstration. More definition occurs as concepts evolve.

Visions of Improvement:

A basic improvement in this criteria would be the redefinition of all TRL requirements to fit the goals of future highly reusable space transportation. Further improvement is implementation and is synergistic with the criteria “number of components with demonstrated high reliability (increase)”. The research, technology and development phases must define goals at subsystem levels that are consistent with the broad goals of the entire transportation system. Testing and demonstration should focus on support requirements such as (1) long life limit, high reliability parts to preclude high levels of replacement costs including manufacture, logistics, handling, dedicated design engineering and launch site infrastructure and support, and (2) customer requirements such as those of potential commercial operators or payload providers.

Target for Improvement:

This is a “pure” design feature targets for which can be established for components and subsystems only *once TRL definitions focused on life cycle costs can be agreed upon by the technical community.*

(17) Number of different fluids (reduce):

Shuttle Benchmark: 16 (majors only)

Derivation:

High numbers of *different* fluids correlate strongly to operation and support costs, the ability to launch on time, the simplicity of the vehicle and to overall supportability, recurring costs and hence life cycle costs.

The Shuttle *uses:

- LO2 and LH2 for main propulsion.
- Fuel cell grade LOX
- Hypergols (N2O4 and MMH) for auxiliary propulsion (OMS/RCS) as well as hydrazine for auxiliary power units (APU's).
- Hydraulic fluid for the actuation of aero-surfaces, landing gear and valves.
- Waterproofing agents (DMES) for tile thermal protection systems.
- Freons (R-114, 21 and 22) for thermal management (indirect and direct cooling of avionics, other systems, crew cabin A/C, as well as ground operations).
- Ammonia (NH3) for thermal management.
- GHe and GN2 for inerting and purges.
- Water for cooling loops (A/C environmental control).
- Freon precision cleaning agent for ground operations.

Other examples include the National Aerospace Plane (NASP) planning which included "liquid hydrogen, liquid oxygen, liquid helium, methanol, silane, hydraulic fluid, polyalphaolefin and liquid nitrogen"[16]. This list does not address NASP planning for thermal management (freons, water) as well as other gases, however these would add to this list of different major fluids to be counted as a concept matures to design and through implementation.

Commonality provides opportunities to eliminate and or simplify separate infrastructure and facility requirements. The integration of vehicle systems required for this is also desirable.

This criteria is extremely synergistic with the "number of toxic fluids (reduce)".

Level: 1 or 2 - This information is usually available early in concept development; however, thermal management may not be defined till later (affecting 5 of the fluids mentioned). This is critical information to decision making that should be required as early in concept development and decision making as possible.

Visions of Improvement:

Basic improvements first address the criteria "number of toxic fluids" and then move on to this criteria. Additions of fluids such as RP1 to LO2 and LH2 as main propellants have negative associated impacts. A system consisting of only RP1, LO2, LH2, GHe, GN2, water, one freon, ammonia and freon PCA would still have 9 of the 16 commodities, 4 of which would be toxic.

Target for Improvement:

This criteria is a "pure" design feature a target for which can be easily established. A target for improvement would be to have LO2, LH2, GHe and GN2, water, one freon, and freon PCA - a total of 7 and less than 1/2 of current Shuttle systems.

*Manufacturing fluids would further increase this number.

(18) Mass fraction required (reduce):

Shuttle Benchmark: To avoid accounting for SRB comparisons the benchmark used here is for an all rocket powered SSTO type vehicle similar to the bipropellant Access to Space[14] baseline Option 3. The basic rocket equation, with Isp limitations and delta-V requirements as constraints, places this number at ≈ 0.90 mass fraction required for an all rocket SSTO.

System	Propellant Mass Fraction
Rocket	
Single Stage	0.88-0.89
Two Stage	0.85-0.86
Combined Cycle Airbreather	
Single Stage	0.65-0.72
Two Stage	0.57-0.64

Table 4: These mass fraction comparisons are not gains of simply "0.2" for airbreathers as possible improvements. Rather they represent a potential tripling of the design space available with associated potential operability gains through more robust, reusable systems. Source: Johns Hopkins University, Applied Physics Lab, Briefing[5], to Space Propulsion Synergy Team by Dr. Frederick S. Billig[4].

Derivation:

Reference "2- System margin (increase)" and "27 - Average Isp on the reference trajectory (increase)".

This criteria may be considered to be the inverse of the prior Isp criteria. Two distinctions are required:

- The criteria is focused on lower mass fractions as enabling more operable, robust systems. Lower mass fractions are only meaningful if they translate into payload and or robustness and operability.
- The increase in Isp is one possible approach to reducing or meeting a mass fraction. A mass fraction criteria stressing reduction is more inclusive of these possibilities.

Higher mass fractions in the 0.90 range cause increased sensitivity to vehicle size (gross lift off weight) in so far as low Isp and Isp variations (such as less Isp resulting during development) are combined. Solutions result in low margins and lack of robustness of the vehicle as performance requirements must be met. This is operationally undesirable.

Level: 1 - Similar to Isp this is information available early in concept development.

Visions of Improvement:

Mass fractions of 0.635 to 0.715 are desirable assuming the gains carry as a side effect more robust, operable systems. The additional systems such as active cooling or more engine modes which may be associated with reductions in mass fraction must be traded against features such as those contained in this guide.

Maximum improvement in mass fraction takes into account not only Isp gains but also the efficiency with which the spaces of a vehicle are designed. The synergy to component reliability is critical. This in turn relates to confined spaces, which are undesirable, purges, which should be eliminated, and the degree of difficulty in accessing areas, which should be minimal. This is not the only criteria related to component reliability in this guide. As with “number of components with demonstrated reliability” or “technology readiness levels” the relation to thorough test and demonstration of operable, long life, reusable and robust characteristics is intrinsically tied to broad advances in operability.

Target for Improvement:

No target has yet been determined here even though this is a “pure” design feature. Optimal design would continue to reduce mass fraction focused on payback and operability of the systems that result in these gains.

(19) Number of systems requiring monitoring due to hazards (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

Shuttle system examples include:

- Closed compartments (monitoring for hazardous gases such as leakage of O2 or H2 during loading as well as monitoring for O2 content during personnel access). This includes the orbiter aft, ET intertank, and, for leakage concerns only, interfaces such as the H2 vent arm carrier plate.
- LOX System temperatures during loading (for geysering effects).
- Cryo tank pressures and intertank temperatures (for maintaining structural margins and load limits).

Level: 2 and 3 - This information is often unavailable in early concept development.

Visions of Improvement:

Monitoring of confined spaces for O2 content can reduce requirements by avoiding a need for access at all. This is synergistic with other criteria such as “number of components with demonstrated high reliability”, “number of hands on activities required”, “number of systems with BIT / BITE” and others.

Basic improvements continue with reductions in loading requirements by using more robust structures capable of safely being loaded at low pressures with minimal vent cycling for cryogenics. For example, a pressurized LOX loading with cycles between 8 and 12 psig could be caused by low robustness requiring pressure to assist structural margins. The system monitoring requirements for temperature and pressure increase as does the degree of hazard associated with the operation. Low pressures and robust tanks are improvements.

Target for Improvement:

This criteria is not a “pure” design feature a target for which can be easily set. It is included here as a critical direction for future systems to improve upon versus Shuttle.

(20) Number of parts (different, backup, complex) (reduce):

Shuttle Benchmark: Indeterminate as of this revision (examples below).

Derivation:

- Complexity: One measure is parts count.
- Commonality: Maintenance, test and checkout procedures and the logistics supply system are simplified.

For one system to be compared against another the level at which the comparison is made must be specified. Levels of complexity may be determined at the component, subsystem, system, element or architecture level. Also, the purpose of the parts can not be separated from the measure of complexity. Additional parts (complexity) may allow greater affordability such as through systems automation or health monitoring, requiring more sensors and lines of code, or it may entail more parts to increase mission reliability, such as engine out return to launch site capability through out ascent. The productivity of each part, it's resulting benefit, is positive. An increase in parts count, meaning increased complexity and opportunities for failures and turnaround expense, is negative. Trades are required which establish these relations across the life cycle of the product.

	Major Component Parts
Space Shuttle Main Engine (SSME)	5,807 [13] / ≈ 4,744* by P/N's for Block 1 Engine 2036
Total for Four (Low and High Pressure) Turbopumps per SSME	2,700 [13]
Piece Part Count per SSME	70,000 [13] / ≈29,000* for Block 1 Engine 2036
Number of Welds per SSME [13, and FMEA/CIL]	≈3000, Phase II Engine
Shuttle Orbiter Thermal Protection System (Tiles and Blankets)	≈27,000

*Table 5: (London 1994)[13], *Rocketdyne Parts List, and FMEA/CIL Statistics.*

Shuttle systems are characterized by a high degree of complexity focused on performance (function) and mission reliability (as through redundancy). The effect of this resulting complexity on operations for turnaround and launch (dependability) was not a design driver. Lack of reliability of individual parts further dictated the addition of processes (inspections, checkouts, tests) that result in low flight rate and high recurring cost.

This criteria is synergistic with other criteria such as "number of components with demonstrated high reliability (increase)", "number of different propulsion systems (reduce)", "number of unique stages (reduce)", "number of active ground systems required for servicing (reduce)", "mass fraction required (reduce)", and the "number of propulsion sub-systems with fault tolerance (increase)".

Level: 3 - Parts count and degree of complexity is information usually developing as the design matures to a preliminary design phase. Early on in decision making the "complexity factor" may not be as clearly understood. However, this is still critical information that should be determined as early as possible in decision making.

Visions of Improvement:

Basic improvement addresses the architecture of the total transportation system incorporating many of the criteria already covered elsewhere in this guide for other reasons. For example, reducing toxic fluids or following a common propellant ground rule allows more commonality of parts. This simplifies maintenance procedures as well as the logistics system.

Further improvement increases reliability both for the flight as well as the turnaround by reducing parts count. For example, the elimination of a system through a creative approach inherently increases reliability during processing (fewer opportunities for failures).

Ideal levels of improvement occur when the productivity of additional systems far outweighs the increased complexity, such as in achieving more valuable functions or qualities (such as loitering or faster turnaround capability). This requires rigorous demonstration, evolution and design iteration aimed at creating hardware with extremely high levels of component reliability. The result is negative "opportunistic failures" during turnaround operations are not as easily accumulated and costly.

- Shuttle replacement of parts on each orbiter per flow varies from 100 to 200 parts per flow. Reference Figure "D" in design feature 10, number of components with demonstrated high reliability.

Target for Improvement:

Two targets can be established here. One is to reduce parts count over Shuttle. This begins to address extremely high operating expenses due to complex systems and the resulting opportunities for failures.

The second, with likely more impact, targets component reliability. Data for current systems (MTBF, Life Limits, Reliability) can be quantified and high targets for demonstrating new designs established. Rigorous qualification and certification in the pre-acquisition phase including tests to failure enables the affordable operation of complex systems.

(21) Number of expendables (fluid, parts, software) (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

For Shuttle this includes numerous fluids. The distinction for this criteria from others already discussed is primarily that it includes "soft goods" such as seals and software. Software is here considered an expendable for Shuttle given the unique flight to flight requirements of parts of the Shuttle software set.

- Softgoods (seals for example, even if not of the "soft" variety such as metallic seals, naflexes, washers). These include flight and ground (regulators, facility, interfaces).
- Software
- Propellants (LO2 and LH2)
- Propellants (Hypergols)
- GHe and GN2
- Hydrazine (auxiliary power units)
- Catalyst (auxiliary power units)
- Hydraulic fluid (flight and ground)
- Cleaning fluids (Freon PCA and others)
- Freons (thermal management)
- Ammonia (thermal management)
- Propane (LH2 flare stack)
- Conditioned air
- DMES (waterproofing agent)

Level: 1 and 2: These values may be determined early in concept development and demonstration. More definition occurs as concepts evolve.

Visions of Improvement:

Assuming other higher priority criteria (such as criteria "1" - toxic fluids, "17" - different fluids or "18" - mass fraction) are addressed then the focus of this criteria becomes primarily softgoods and software.

Basic improvement in the use of softgoods would address (1) component reliability (criteria "10") and (2) interfaces (criteria "30").

Ideal levels of improvement would have been achieved when the servicing of main propellants is the only expendable from flight to flight.

Target for Improvement:

This criteria is a "pure" design feature which represents actual materials to account for.

Targets for improvement in this criteria are synergistic with improvements in other areas such as "number of toxic fluids (reduce)", "number of different fluids (reduce)" and "number of purges required (reduce)". Improvement may target one servicing operation of main propellants, limited use of gases such as GHe and GN2, no hydraulic fluid servicing from flight to flight, no additional fluids for power, no waterproofing or special coatings, and no highly unique software loading or reconfiguring from flight to flight.

(22) Number of checkouts required (reduce):

Shuttle Benchmark: High - indeterminate as of this revision.

Derivation:

- The term “checkout” indicates functional, dynamic verification as distinct from inspections (criteria 23).

Where there is no automated VHM system available as on Shuttle the functional verification must be performed to establish the reliability of a component or system. This includes all redundant components and systems which are required to provide fault tolerance of critical functions. On Shuttle these include, but are not limited to:

- Valves (for back flow if check valves, for actuation including timing, internal leakage, and flowrate verifications).
- Electrical systems (using intrusive breakout boxes to perform checkouts given the high number of electronic systems with no BIT / BITE).

Level: 3 - Information on the checkouts that will be required requires information that may not be available early in concept definition.

Visions of Improvement:

As other criteria are improved upon, such as fewer toxic fluids, more BIT / BITE, fewer highly critical conditions such as confined spaces requiring purges, fewer active ground systems for servicing, and fewer potential leakage and connection sources, then improvements will accumulate in this criteria (fewer checkouts.)

Basic improvement requires that not only in flight reliability of components be increased but that it be done without use of processing intensive inspection or checkout to isolate, repair and replace faulty components pre-flight. Rigorous certification focused on robust, dependable, maintainable as well as reliable systems is required. High reliability *and* reusability are both required to assure reductions in the number of checkouts.

Target for Improvement:

This criteria is not a “pure” design feature that is easily targeted. It is a resultant of features already listed such as the high ranking criteria number 10 - number of components with demonstrated high reliability. Targets may be set upon a full understanding of the criticality, complexity and demonstrated reliability of components especially the robustness of systems and the reliability demonstrated during processing.

(23) Number of pollutive or toxic materials (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

The distinction here from toxic fluids, a much higher ranked criteria, is in the greater correlation to processing (safety and supportability) and recurring costs associated with the fluids rather than the expended materials. Both are related. Materials here represent primarily a recurring cost impact due to regulated waste management and disposal of hazardous materials.

These include contaminated fuels, cleaning solutions, primers, paint strippers, lubricants, post launch waste water, hypergolic scrubber fluids, as well as materials impregnated with any of these fluids.

Level: 2 and 3 - Information on this criteria is usually not available early in concept development. As the design matures this information can be used to assess the likely supportability of a concept.

Visions of Improvement:

Basic improvement addresses cleaning requirements the processes for which generate highly regulated waste. This in turn relates to the size of infrastructure, the replacement of components on ground systems many of which have stringent cleaning requirements and the degree of intrusion into systems.

Target for Improvement:

This criteria is a pure design feature targets for which can be established focusing on existing quantities of pollutants and setting new levels as well as materials replacement schedules based on these data.

(24) Number of inspection points (reduce):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

- Inspection here is used to refer to establishing a level of accomplishment such as the degree to which a product has met objectives or acceptability to design specifications.

Shuttle inspection points include:

- Orbiter TPS (Tile, carbon-carbon, after each flight)
- SSME MCC / nozzle (step and gap for thermal damage)
- SSME turbopumps (bearing degradation, torque checks, end travel check, nozzle burn through)
- Orbiter structure (cracks, corrosion, OMDP only)
- Orbiter windows (inspected and polished every flight)
- Orbiter brake system (wheel and tire)
- Orbiter payload bay radiators (every flight for space debris)
- Orbiter cold plates (for degradation of surface finish or damage during component removal and replacement)
- ET TPS debonds (foam, pre-flight)
- Orbiter composite structure degradation
- Internal corrosion in fluid systems (example: water flash evaporator, thermal management systems)
- Interfaces for sealing surface finishes, damage and coatings (For example, ET to Orbiter 17-inch disconnects, SSME to MPS, every flight)
- ET / Orbiter 17-inch disconnects (every flight, every ET set even though new, every Orbiter set even though reused)
- Orbiter MPS screens for debris
- OMS / RCS inspections for nitrate buildups
- Hydraulic fluid filters
- Inspect for hydraulic leaks visually

Multitudes of other requirements to visually inspect an area and verify an acceptable condition exist for Shuttle.

Level: 3 - More detailed information that is available as the design matures to a preliminary design phase and beyond.

Visions of Improvement:

Basic improvement on this criteria is synergistic with the “number of components with demonstrated high reliability (increase)”. While in flight reliability for Shuttle systems may be relatively high (for space systems) it is assured in part by inspections for critical systems during turnaround. The more numerous the inspection requirements the higher the manpower required to accomplish work within a given flight rate. Process reliability, the reliability during turnaround, if low, dictates high numbers of mandatory inspections to assure components are ready for the next flight, or to assure that all failed components are found and repaired, replaced or have problems adequately addressed.

Robust development, providing both high reliability in use as well as high life limits for reusability, relates directly to this criteria. Definition of a development plan including test, design iteration, targeted reliability and life limits is required.

Target for Improvement:

This criteria is a “pure” design feature an adequate understanding of which would be obtained upon quantifying inspection requirements on Shuttle such as through the review of OMRS documents. It is also a resultant of the degree to which other features listed are improved upon or not. The ideal target is to require no more than a simple walk around of a future highly reusable space transportation system, hence approaching aircraft type operations.

(25) Number of propulsion sub-systems with fault tolerance (increase):

Shuttle Benchmark: Indeterminate as of this revision.

Derivation:

Current Shuttle systems increase complexity for certain critical functions in order to assure a higher reliability in flight.

For example, the Shuttle hydraulic system is triple redundant to avoid loss of control of main engine functions such as thrust vector control. For the SRB's double redundancy is used in hydraulics. Auxiliary propulsion (OMS /RCS) is cross fed to provide certain backups. Power systems (APU's ≈ 135 Hp each) are triple redundant under nominal operation. A simple example is the use in many systems of quad redundant check valves (series and parallel) or dual redundant filters (in parallel) to assure proper flow and function. This is all desirable from the perspective of fault tolerance; however, complexity increases if defined by parts count and processing activity increases due to more opportunities for failure.

Level: 2 - Information usually not available early on in concept definition.

Visions of Improvement:

To assure fault tolerance increases without impacting operations a demonstrated high reliability per component is required. Basic improvements in fault tolerance must be coupled to the reliability of components during turnaround, often called process reliability or supportability. This criteria is synergistic with "number of components with demonstrated high reliability (increase)". Basic improvements would require (1) simplification of systems, (2) fault tolerance through increased margins and robustness for operation, and (3) a thorough research, development and demonstration focused on high component life limits (millions of cycles, millions of minutes, component lifetimes near to vehicle lifetimes) and (4) the iteration on designs, tests to failure, improvements in reusability including ground and flight operation.

Target for Improvement:

Targets for this criteria require a comparison by components to similar components on a system such as Shuttle. Comparisons to commercially similar equipment can also serve as targets. Further, for new components in next generation systems the target can be established with a comparison or "sanity check" to the operational goals and life cycle cost goals for the system.

(26) Number of engines (reduce):

Shuttle Benchmark: 3 SSME's, 2 OMS engines, 2 SRB's

Derivation:

- An engine is defined as: The number of discrete propulsion sets that are individually delivered or installed or that are individually overhauled. Equals the number of engines for conventional bell nozzle rocket engines.

The number of engines is a multiplier of maintenance and test requirements for any given configuration. Where more engines are used to reduce power levels, enhancing life limitations on components and increasing reusability, there is a benefit. Being able to achieve that *same benefit with fewer engines* is always desirable. This is synergistic with the criteria "number of components with demonstrated high reliability (increase)".

	Engines	Total
Atlas IIAR (Liquid, Centaur)*	1, 1	2
Access to Space Airbreather / Rocket	2+2	4
Shuttle (Main Propulsion, SRB's, OMS)	3, 2, 2	7
Atlas IIAS (Liquid*, Liquid, Solids, Centaur)	1, 1, 4, 2	8
Access to Space All Rocket Bipropellant SSTO (Main and OMS)	7, 2	9
Saturn Apollo Moon Rocket (Stage 1, 2, 3, 4)	5, 5, 1, 1	12
Soviet N-1 Moon Rocket[3] (Stage 1, 2, 3, 4, 5)	30, 8, 4, 1, 1	44
*2 Thrust chambers per engine Note: Varying payload, launch rate capabilities, staging events. *Italics = Planned or conceptual, not flown.*		

Table 6: Various engine count examples. Note that a requirement for "engine out" capability possibly increases the number of engines for a vertical take-off rocket whereas with horizontal take-off, imposing the same requirement, it is still possible to reduce engine count.

The number of engines on a vehicle is strongly related to the ease of integration and the maintainability of the propulsion system.

Level: 1 - This is information available early in the conceptual phases of vehicle definition.

Visions of Improvement:

Basic improvement begins by altering the definition of an "engine". The sharing of components, such as at the turbopump level should a failure occur, begins to reduce parts count or to provide more fault tolerance. Reduced power levels are required to enable this. Further, integration, combined with increased throttle capability and control, could eliminate separate systems for orbital maneuvering such as the 2 Shuttle OMS pods. This is synergistic with reducing the number of different fluids which also enables fewer active ground systems for servicing.

Ideal levels of improvement would be enabled by a few high reliability engines. Similar to aircraft, the number of engines could be a targeted architectural feature once highly reusable space transportation is enabled similar to airline preferences for twin jet aircraft versus aircraft with 3 or more engines.

Target for Improvement:

Targets for improvement over the current 3+2+2 configuration could (1) target commonality (of fluids, hardware, tankage) and then (2) target fewer remaining engines.

(27) Average I_{sp} on the reference trajectory (increase):

Shuttle Benchmark: To avoid accounting for SRB's the benchmark used here is for an all rocket powered SSTO type vehicle similar to the bipropellant Access to Space[14] baseline Option 3. The value for an SSME type performance is 430s (about 370s at sea level and 450s in vacuum).

	I^*
SSME type	375sec
Ejector Scramjet type	645sec

Table 7: Comparison of rocket versus rocket based combined cycle (RBCC) systems using an I^* method (Escher 1995)[10].

Derivation:

Shuttle or subsequent possible all rocket SSTO vehicles have low effective Isp. This has various implications: (1) higher mass fractions required (0.90), (2) increased sensitivity to vehicle size (gross lift off weight) and (3) increased risk to payload targets not being met during development. All of the prior can be considered as resulting directly or indirectly in low robustness of a vehicle.

High Isp gains enable mass fraction requirements as low as 0.6 to 0.7. Effective Isp of 700-800 s begins to enable these targets. Much enhanced operability is a side effect through the allowance of more robust, operable systems on the vehicle that may be enabled by the lower mass fraction.

Level: 1 - Usually available as information very early in any concept development.

Visions of Improvement:

The high rank here assumes dramatic Isp gains. Associated improvements could include:

- More robust thermal protection systems (assuming passive only) enabled by less weight sensitivity in development.
- Powered approaches for landing and self ferry.
- Higher margins in major subsystems such as propulsion down to the component level.
- Operating ranges well below design tolerances eliminating the practice of running engines at > 100% of rated thrust. This extends life limits resulting in more supportable, less manpower intensive systems.

Target for Improvement:

This criteria is a “pure” design feature; however, a technology development effort that must assure closure of the performance aspects must creatively integrate these with the guidelines contained here for maximum operational and programmatic (pre-operational) benefit. Hence, Isp gains consistent with these guidelines should be targeted.

(28) Number of manhours (c/o, handle, assemble, etc) on system between LCF/HCF (reduce):

Shuttle Benchmark: High - indeterminate as of this revision.

Derivation:

LCF (low cycle fatigue) and HCF (high cycle fatigue) are contributors to component failures. Low values for life limits mean little reusability and hence lack of affordability due to inspection, checkout, test, repair or replacement of LRU's. On/off cycles create transients on high pressure turbomachinery for example which limit reusability in the propulsion system. Duration or wear due to extended use can also limit reusability if high cycle life is low. Safety factors that are relatively high (1.5, 2 or 4) do not always correlate to high reusability and should not be taken as an indication of robustness (for example use of a component to ½ of fleet leader failure experience).

Manhours and costs accumulate as components with low reusability require attention on a system such as Shuttle. This criteria is a subset to "9 - number of components with demonstrated high reliability (increase)" given the limitation here to only LCF and HCF problems.

Level: 3 - More detailed information that is available as the design matures to a preliminary design phase.

Visions of Improvement:

Improvement here includes:

- Robustness and margin
- Certification (qualification) practices
- New technologies

Increased power level margins on engines begin to increase life limits on propulsion systems, a major cost component of any space transportation system. An example is design and development of an engine at a 100% power / thrust level but using it at only 75% of this rating. Preserving this margin during development is a priority for improvements in this criteria.

Certification (qualification) practices require definition. A major programmatic cost driver is the iteration of designs, tests to failure and redesigns for increased life cycle limits addressing either LCF or HCF. Programmatics dictate:

1. Identifying those systems with life limits driven by LCF/HCF.
2. Identifying costs associated with these systems.
3. Focusing certification on extending life limits for those systems with the highest portion of life cycle costs.

More advanced improvement address LCF/HCF using new technologies. Examples here include fluid film bearings or laser ignition for turbomachinery, new materials and manufacturing techniques.

Target for Improvement:

This criteria is partially a resultant of other features contained in this guide. It is also a “pure” design feature targets for which can be established based on similar systems such as those on Shuttle. A detailed breakdown of systems and components (by part) and an analysis of design, repair and maintenance data for LCF/HCF causes is required. Correlations of major cost elements to systems with low reusability are required. Current accounting methods for Shuttle problem tracking do not accomplish this. No comprehensive study has addressed this to date.

(29) Number of criticality 1 failure modes (reduce):

Shuttle Benchmark: Shuttle criticality 1 failure modes are Orbiter ≈ 1700, Solid Rocket Boosters ≈ 2200, External Tank ≈ 1100, Shuttle Main Engines ≈ 800, and GSE ≈ 300. Criticality 1R failure modes are Orbiter ≈ 6300, Solid Rocket Boosters ≈ 1300, External Tank ≈ 100, Shuttle Main Engines ≈ 400,and GSE ≈ 400 (*from Critical Hardware Lists, JSC)*.

Derivation:

Criticality 1 failure modes are defined as “loss of life or vehicle”. Where redundancy exists but loss of both redundant items could cause loss of life or vehicle the designation is 1R. Criticality 1 failure modes correlate strongly to personnel and public safety. For Shuttle a FMEA / CIL approach is used to manage risk by identifying and formally documenting potential and critical failures.

Level: 2 and 3 - This information is usually not expected in early concept definition.

Visions of Improvement:

A vision of improvement is sufficient redundancy or simplicity to reduce criticality 1 failure modes to a fraction of current Shuttle levels *while simultaneously improving on the total system reliability during processing.* Functionality, the usefulness of the system to a payload customer, being flexible or having generous capacity, would also be simultaneously improved upon.

Target for Improvement:

This criteria is a “pure” design feature which represents actual hardware that can be accounted for. Improvement here may be measured against complex Shuttle systems. Improvement here must be synergistic with top criteria such as “number of systems with BIT / BITE (increase)”, “number of active ground systems required for servicing (decrease)”, “number of components with demonstrated reliability (increase)”, and “number of parts (different, backup, complex) (decrease)”. Targeting reductions in criticality 1 failure modes without addressing these other criteria would adversely affect process reliability resulting in increased turnaround and operating costs.

Design Features (30 through 64)

Further expansion on all the design features, such as with the measurable criteria 1 through 29, will be done in future reports. The SPST will continue to support efforts relating to space transportation by exploring questions and answers key to future decision making. The remaining criteria are:

30. # of element to element interfaces requiring engineering control (-)
31. Hours to refurbish propulsion system (-)
32. # of physically difficult to access areas (-)
33. % of propulsion subsystems monitored to change from hazard to safe (+)
34. # of hours to refurbish launch site between each launch (-)
35. Mean time between major overhaul (-)
36. Amount of energy release from unplanned reaction of propellant (-)
37. # of manufacturing, test and operations facilities (recurring) (-)
38. # of ground power systems (-)
39. # of active engine systems required to function (-)
40. Margin, mass fraction (+)
41. Mean time between major overhaul as % of cost of system (+)
42. Amount of real time inspection or repair (-)
43. # of hazardous processes (-)
44. Margin, thrust level / engine chamber pressure (+)
45. Hardware cost (-)
46. # of major systems required to ferry or return to launch site (plus logistics support) (-)
47. # of modes or cycles (-)
48. # of alternate dedicated emergency abort sites required (-)
49. # of engine restarts required (-)
50. Margin, average specific impulse (+)
51. # of keepout zones (-)
52. # of aero-control surfaces (-)
53. # of cleanliness requirements (-)
54. Facility capitalization cost (-)
55. Cost of transportation / requirements (-)
56. % of trajectory time available for abort (+)
57. Amount of response time to initiate safe abort (-)
58. # of tools required (-)
59. Margin, % of payload (+)
60. # of process steps to manufacture (-)
61. # of attainable destinations (+)
62. Ideal delta-V on reference trajectory (-)
63. # of acres permanently affected (-)
64. # new unique approaches (+)

Design Features (30 through 64) - Definitions

The following are brief definitions and clarifications of the prior design features.

- Note: (-) Indicates the desirable direction is to reduce.
  (+) Indicates the desirable direction is to increase.

30. # of element to element interfaces requiring engineering control (-): This feature includes major interfaces between distinct organizations. On Shuttle for example, orbiter to SSME and orbiter to ET interfaces correspond to distinct centers and contracts. Internal but still formal interfaces incur the recurring costs of configuration control, documentation and organizational or customer interfaces.

31. Hours to refurbish propulsion system (-): Includes all systems, not just the engines. Propellant tanks and associated systems, feedlines, main propulsion, controllers and sensors are included. Also includes the interfaces from any facilities such as propellant feeds or vents, electrical interfaces and any other fluid requirements (such as purges). This criteria is a resultant of other features listed in this guide such as the high priority criteria on toxic fluid count, the degree of BIT / BITE, or the number of components with demonstrated high reliability.

32. # of physically difficult to access areas (-): Any area requiring more than reasonable access. An example is the Shuttle orbiter aft, requiring access kit installation and great care accessing the area. Little space is provided for error such as a missed step. Crawling in uncomfortable positions is the norm.

33. % of propulsion subsystems monitored to change from hazard to safe (+): Any potential hazards should be monitored in the propulsion system and in some way changed as required to a safe configuration.

34. # of hours to refurbish launch site between each launch (-): Includes the facility as well as the interfaces to the vehicle (feeds, vents and electrical as well as other fluids). This criteria is a resultant of other features listed in this guide such as high priority criteria on toxic fluids count, the number of purges, the number of leakage or connection points and the degree of BIT / BITE.

35. Mean time between major overhaul (-): Depot maintenance operations reduce fleet productivity. The desirable direction is a high number of flights between any required major downtime.

36. Amount of energy release from unplanned reaction of propellant (-): Measured by quantity of propellant such as cryogens, hypergols or any others such as RP-1 or any propellants for auxiliary propulsion or station keeping.

37. # of manufacturing, test and operations facilities (recurring) (-): For Shuttle this includes external tank (ET) production and SRB/SRM manufacture and continuing refurbishment. It also includes engine test facilities. Operations facilities include the launch site such as processing hangers, landing sites, and pads.

38. # of ground power systems (-): For example a ground power transmission station or a dedicated electrical power generating facility.

39. # of active engine systems required to function (-): Similar to the "number of active components required to function including flight operations (reduce)" except considering only the engine, a subset of the propulsion system.

40. Margin, mass fraction (+): Given a mass fraction requirement it is desirable both during development and into implementation to carry margin on the mass fraction. For the purposes of this guide the mass fractions are assumed to be low, a higher priority (reference criteria 17-Mass fraction required (reduce)). For example, a concept requiring 0.70 mass fraction but developed and implemented at a value of 0.72 would have margin. This would be similar to the use of 15% weight growth margins in development so as to avoid the undesirable effects of inevitable weight growth. These undesirable effects in development and implementation include (1) loss of robustness, (2) increased thrust power levels on engines (3) loss of payload. The ability to implement with mass fraction margin allows greater flexibility (such as greater payload) at less cost for the transportation system at a later point if required.

41. Mean time between major overhaul as % of cost of system (+): For an expensive component, relative to the whole system, the mean time between major overhaul should be increased (as in more reusability).

42. Amount of real time inspection or repair (-): Measured in manhours. Robust systems requiring no inspection or which in some way reduce the processing tasks manpower intensive nature are desirable. Functional, in use verification is desirable where such use is truly indicative of the health of the system. This criteria is a resultant of other features listed in this guide.

43. # of hazardous processes (-): This includes lifting operations, toxic fluids, complex loading scenarios and use of purges.

44. Margin, thrust level / engine chamber pressure (+): Given a GLOW the development and implementation of a system with thrust levels well below those designed, tested and certified to is desirable. For example, a design may be certified at 100% but used only at 75% power levels. Increased reusability of propulsion systems components

and hence operability of the system results. Combined with other approaches reusability of the propulsion systems increases.

45. Hardware cost (-): The actual cost of a component such as a spare that is required to continue operations. Does not include the handling, tracking and analysis associated with that part, or the work to actually replace the component and verify a successful repair.

46. # of major systems required to ferry or return to launch site (-) (plus logistics support): Includes any dedicated ferry craft (such as the Shuttle 747), all facilities such as a mate de-mate facility or any contingency equipment.

47. # of modes or cycles (-): Air breathing rocket, ram, scram, pure rocket as well as any changes such as from RP-1 to LH2 constitute a mode or cycle.

48. # of alternate dedicated emergency abort sites required (-): Does not include an alternate site if that site is not dedicated to the abort contingency.

49. # of engine restarts required (-): Restarting of engines, to the extent it can be avoided, is not desirable; however, this is secondary to the higher priority criteria "5 - number of different propulsion systems (reduce)".

50. Margin, average specific impulse (+): Given an engine Isp the use at a lower Isp value is desirable allowing flexibility or capability for the transportation system. For the purposes of this guide the Isp is assumed to be high, a higher priority (reference criteria 26-Average Isp on the reference trajectory (increase)).

51. # of keepout zones (-): Hazardous loading operations, purged confined spaces and toxic propellant storage areas are included in this count. Keepout zones often interfere with other required operations.

52. # of aero-control surfaces (-): Includes body flaps, rudders, ailerons, elevons and any other actuated or active surface.

53. # of cleanliness requirements (-): Includes any requirements for handling, particulate, non-volatile residue, storage, component cleanliness, maintaining clean levels, blow downs, filters, analysis, manufacture, assembly and operations.

54. Facility capitalization cost (-): Dedicated facilities infer a high cost to operate a system and to maintain it on a recurring cost basis.

55. Cost of transportation / requirements (-): Any dedicated transportation requirements such as equipment, special handling or transportation of components for manufacture.

56. % of trajectory time available for abort (+): The ideal is an abort capability from engine ignition through any part of the flight. An engine out capability from engine start with 100% of trajectory time available for abort is desirable.

57. Amount of response time to initiate safe abort (-): The time required to automatically respond to an abort condition and safe a vehicle should be reduced to the least time possible.

58. # of tools required (-): For operation, dedicated tool requirements such as unique shop tools, wrenches and aids.

59. Margin, % of payload (+): Reference criteria “39” - margin, mass fraction, “43” - margin, thrust level and “49” - margin, average Isp. The establishment of margin in payload capability serves as a forcing function in development avoiding implementation of systems with payload preservation at the expense of robustness, reusability or operability. For example, a targeted 23,000 lbm payload to a given orbit may be used to initially develop and analyze a concept for closure (affecting implementation decisions) even though 20,000 lbm is the eventual requirement. This is distinct from the 15% weight growth margin traditionally used in concept development.

60. # of process steps to manufacture (-): Includes cleaning, welding, X-Rays or other NDE, assembly, coatings, materials manufacture such as autoclaves, hardening, and finishing and or any unique points in the manufacturing process.

61. # of attainable destinations (+): References orbits and cross range capability.

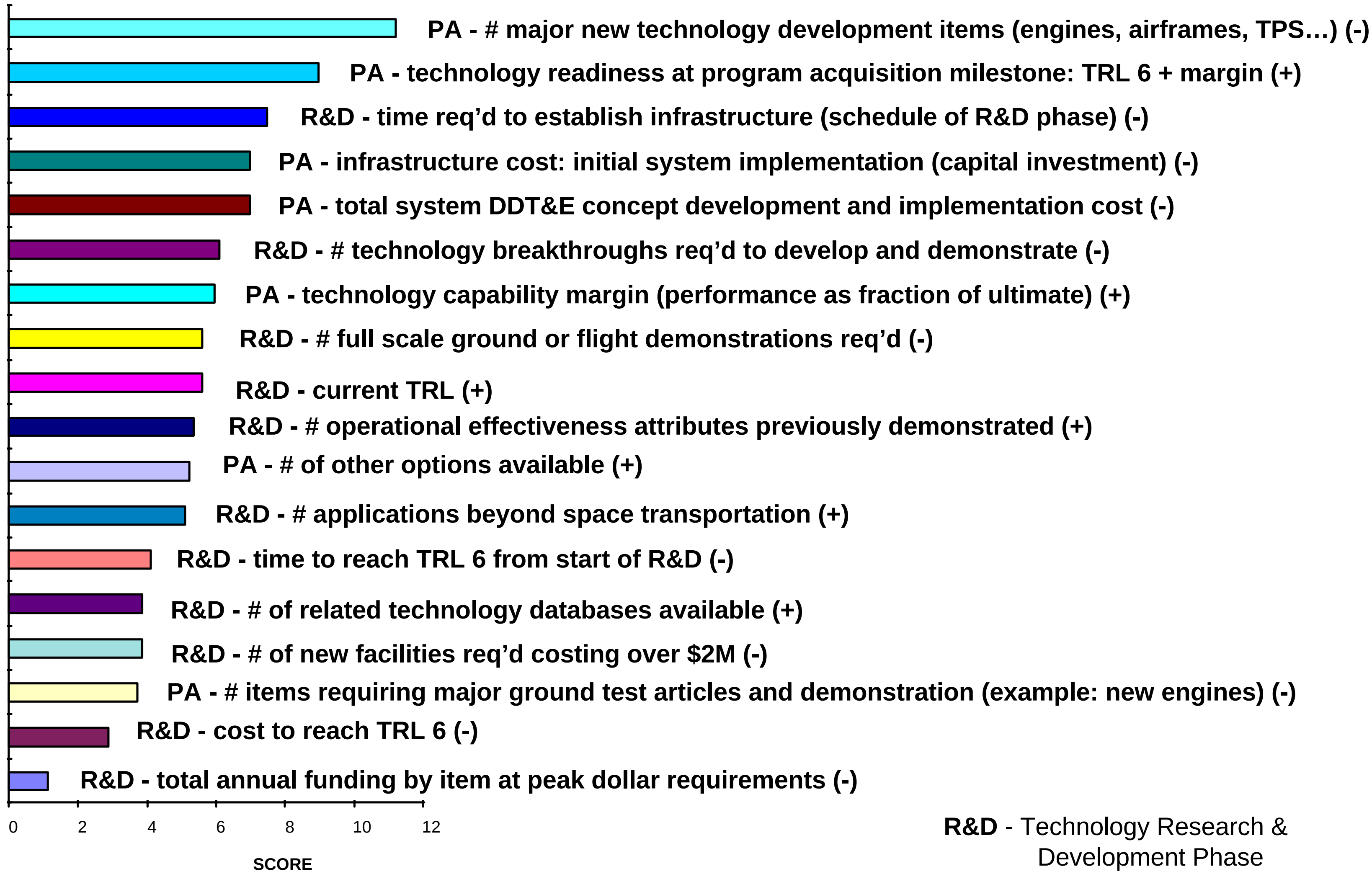
62. Ideal delta-V on reference trajectory (-): Gains from air launches, speed as well as gravity, gains from nozzle underexpansion avoidance, and improved Isp, or speed gains from any launch assist provide a reduction here. This efficiency of configuration characteristic enables comparison of different concepts. A full analysis of the vehicle and it’s forces while flying the reference trajectory is required.

63. # of acres permanently affected (-): Includes operations as well as any dedicated manufacturing capability.

64. # new unique approaches (+): This is from a public perspective only, the novelty of the approach or the public appeal.

Figure 4: Prioritized Measurable Criteria

PROGRAMMATIC



R&D - Technology Research & Development Phase
PA - Program Acquisition Phase

Programmatic Considerations

As previously noted a comparative assessment of space transportation system concepts or design choices within a system must address not only measurable design criteria but also programmatic considerations. The value of this approach has been discussed in the introduction to this document. This section addresses the specific programmatic considerations or factors (as shown on the previous page as well as visualized on the X-axis of the figure on page 2). These programmatic considerations impact the non-recurring cost portion of the life cycle cost of a space transportation architecture. Further these non-recurring costs may be divided into those involved in the R&D phase and those in the program acquisition phase.

The programmatics outlined here cover the traditional categories of program management activities such as cost, schedule, technical, risk, and procurement.

<u>DEFINITIONS</u>

R&D - TECHNOLOGY:

The technology “R&D” category of programmatic considerations is the first major non-recurring cost step leading to “Program Acquisition”. An aircraft production analogy would be the technology R&D in composite materials and structures, CRT flight instruments, and upgraded turbojet engines required to enable a new state-of-the-art transport such as the Boeing 777. Technology R&D must be identified and established as possible “upfront” before a manufacturing decision (program acquisition) is committed.

The following list of programmatic considerations include 11 related to the R&D phase of a program.

PROGRAM ACQUISITION:

“Program Acquisition” is the final non-recurring-cost, major program activity, leading to the fabrication and delivery of the desired “affordable” space transportation system. This “system” includes the delivered vehicles as well as required support infrastructure. An aircraft production analogy would be the data gathering and decision-making process leading to major capital (non-recurring) investment in factory facilities, tooling, and operations-support infrastructure necessary to support production and delivery of aircraft to the customer.

The following list of programmatic considerations include 7 related to this program acquisition phase of a program.

The following describes and clarifies features of any program in an order prioritized using previously described methodology.

"Level" refers to the level or phase in the acquisition cycle at which the desired programmatic information is available. Level 1 is concept definition, 2 is system and subsystem description and 3 is at the preliminary design review phase.

(1) PA - Number of major new technology development items (engines, airframes, TPS…) (reduce):

The system requiring the greatest quantity of new items to develop can be expected to have a much higher risk to the schedule and cost of eventual acquisition.

Level: 1 - This represents information traditionally available early in concept development.

(2) PA - Technology readiness at program acquisition milestone: TRL 6 + margin (increase)

Assessment for the program acquisition phase includes evaluating all the technologies that were researched, developed and demonstrated and then determining if a particular technology will be part of the acquisition or not. For example, a technology at TRL 8 at the time of preliminary program acquisition decisions is more desirable than one at TRL 6 all other factors being equal.

Level: 3 - This represents information that may not be available until later in decision making, such as at a PDR phase.

(3) R&D - Time required to establish infrastructure (schedule of the R&D phase) (reduce)

Infrastructure here refers to major test facilities for R&D requirements such as wind tunnels or test stands. Those concepts requiring a relatively short period of time for the accomplishment of the R&D phase are more attractive than those requiring many years to complete. The measure is in years.

Level: 1 through 3: Partial information and estimates may be available for this information early in concept development. More information becomes available as the project proceeds into a preliminary design phase.

(4) PA - Infrastructure cost: initial system implementation (capital investment) (reduce)

This cost represents a major non-recurring financial investment for system support facilities, equipment and other amortized physical plant properties.

Level: 1 - This represents information traditionally available early in concept development.

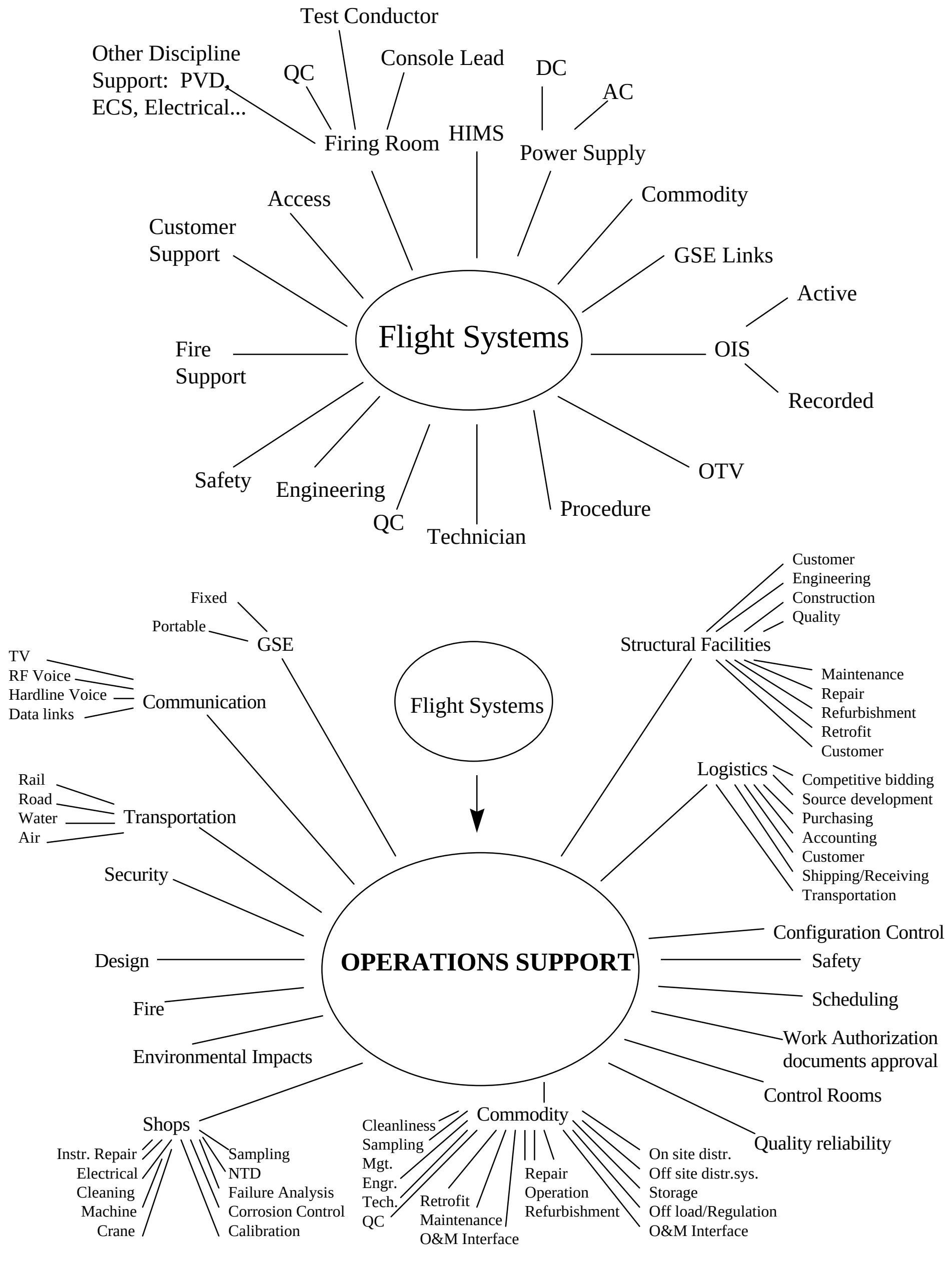


Figure F. The relation of flight systems to eventual infrastructure (NASA OEPSS 1992)[17].

(5) PA - Total system DDT&E concept development and implementation cost (reduce)

This is a prime cost estimate factor (not including infrastructure) which will weigh heavily in go-no-go program acquisition decisions. DDT&E and implementation refers to Design, Development, Test and Engineering as well as the theoretical first unit (implementation) which encompasses first vehicles as well as operating sites.

Level: 1 - This represents information traditionally available early in concept development.

(6) R&D - Number of technology breakthroughs required to develop and demonstrate (reduce)

How many basic physics, materials or performance technical breakthroughs must be developed and demonstrated? Those technologies requiring a greater quantity of “proof of concepts” can be expected to have a higher schedule and program risk.

Level: 1 - This represents information traditionally available early in concept development.

(7) PA - Technology capability margin (performance as fraction of ultimate) (increase)

The resulting fraction can enable an adequate assessment of technical performance margin deemed essential for a robust, affordable system. An example is an engine that can perform the mission at 90% of the maximum rated chamber pressure rather than 106%. The expectation of being able to create, preserve and implement this margin is the program consideration.

Level: 2 through 3: Information in this criteria is traditionally available as the project matures to a PDR phase.

(8) R&D - Number of full scale ground or flight demonstrations required (reduce)

This refers to the development and demonstrations in full scale (system, sub-systems, components) required during the technology R&D phase. The cost of facilities, GSE, material, technical support and headcount relate strongly to the number of demonstrations required.

Level: 2 - This represents information often available early on before any PDR phase.

(9) R&D - Current TRL (increase)

As with the design features (reference design feature 16-Technology Readiness Level) the determination of where a technology is relative to TRL descriptions is a key determinant of placing further emphasis on one approach versus another. The programmatic applicability is generally concerned with technologies at the low end of the TRL spectrum as measured against each other for similar functions.

This criteria, while also used as a design feature, has a different implication from a programmatic perspective. The programmatic concern is the risk to the R&D schedule as well as cost containment.

Level: 1 - This represents information traditionally available early in concept development.

(10) R&D - Number of operational effectiveness attributes previously demonstrated (increase)

A determination of readiness from an operational perspective may not always equal a determination of readiness from a purely functional perspective. A functional perspective may involve only the mission or performance aspect, such as a thermal protection system capable of withstanding certain temperatures or of reliably protecting a vehicle from either ascent or descent heating environments. An operational perspective will go further and include the ability to perform at low or zero levels of turnaround support, with true reusability and robustness.

A technology which has demonstrated operational systems effectiveness would be more desirable than one having demonstrated fewer. Operational systems effectiveness may be measured by having demonstrated attributes such as affordability, reliability, dependability, simplicity, or maintainability. A complete list of desirable attributes is contained in “Overview of the SPST Approach” under “Benefits (Technical)”.

Level: 1 through 2: This represents information often available early before a PDR phase.

(11) PA - Number of other options available (increase)

A particular technology may fulfill a function that may also be achieved with a competing technology. For example, high density fuel cells and batteries may both be available as a power source system at acquisition yet only one may be needed. Having multiple options is desirable for any functional need of a space transportation concept. Program acquisition is enhanced by having varied choices possible to proceed into as well as backups should later events require a redirection.

Level: 1 through 2: This represents information often available early before a PDR phase.

(12) R&D - Number of applications beyond space transportation (increase)

The ability to gain support, private, public or otherwise sponsored for a technology endeavor, increases as the number of possible secondary applications increases. Can the technology be applied to aircraft, trains, automobiles or other areas outside of space transportation systems?

Level: 1 through 2: This represents information often available early before a PDR phase.

(13) R&D - Time to reach TRL 6 from start of R&D (reduce)

Overall program schedule requirements will be affected by upfront R&D timelines. For any technology the ability to reach TRL 6 quickly is desirable.

Level: 1 through 3: Partial information and estimates may be available for this information early in concept development. More information becomes available as the project proceeds into a preliminary design phase.

(14) R&D - Number of related technology databases available (increase)

In assessing levels of risk for budgets, performance, operability and schedule those technologies reasonably well related to documented R&D from previous work should encounter a minimum, predictable level of program risk. “How good is the database?” and “has this been done before or is it all new?” are key questions.

Level: 1 - This represents information traditionally available early in concept development.

(15) R&D - Number of new facilities required costing over $2M (reduce)

This item serves as further quantifier of technology R&D that may likely contribute to an unacceptable level of overall program affordability. This includes test sites and manufacturing sites related to R&D.

Level: 3 - This represents information that may not be available until later in decision making, such as at a PDR phase.

(16) PA - Number of items requiring major ground test articles and demonstration (example: new engines) (reduce)

Major ground test articles are extremely consuming of time and resources. The technology meeting a majority of all other requirements and possessing the least test requirements can be expected to have a cost and schedule advantage.

Level: 1 - This represents information traditionally available early in concept development.

(17) R&D - Cost to reach TRL 6 (reduce)

This measure is in cost. Assuming a set of options or technologies will likely achieve an equal benefit, measured against the design features in this guide for example, then the option which costs less to reach a TRL at which a program acquisition point can be made is more desirable.

Level: 1 - This represents information traditionally available early in concept development.

(18) R&D - Total annual funding by item at peak dollar requirements (reduce)

The measure here is cost. The percent of a programs annual funds required by a particular technology R&D effort is preferably low all other factors being equal.

Level: 1 - This represents information traditionally available early in concept development.

Summary and Conclusions

The intent of this report is a dynamic document providing a framework which will be updated as more data is gathered, improvements are implemented in current systems and new systems are developed and demonstrated.

This document is focused on the HRST study - “to identify innovative new systems concepts that can achieve Earth-to-orbit (ETO) transportation at costs of $100-$200 per pound payload”. These costs are now approximately $5,000-$8,000. With few exceptions the features and the priority order presented in this report are also very applicable to any new space transportation system and to the Shuttle program and any future upgrades it may implement. The identification of concepts and associated technologies that hold the greatest promise of achieving very low recurring costs in space transportation results in critical up front investment decisions. Understanding how system choices relate to eventual recurring costs is a critical part of any up front planning.

The SPST challenges the technical community developing new systems to compare the features of their systems to the features, especially the design features, contained in this guide. The same basic questions apply to a system or an entire concept.

- Are many of the first 10 design features being improved upon?
- Are many of the first 20 design features being improved upon?
- Is a design responsive to the most important programmatics but not the most important design features?
- Is an effort focused on functional performance or is a balanced approach being used which addresses the design features as well as programmatics?
- Have other disciplines been directly involved early on in determining the direction of a technology development - what should be developed and focused on? Has manufacturing been involved early on well before implementation? Have operators been involved in setting a development focus?

Even if the prior questions are not easily answered (such as assessing a concepts improvement against the design features) is the general thrust or direction of a concept responsive to many of the top design features?

This document may be used by designers or program managers in terms of general thrust or direction even if a full assessment against the recommended improvements in order of priority is not immediately possible. The emphasis here is strategic.

Various conclusions are possible at this point:

1. The questions contained in each of this guides design features (how many toxic fluids, how much potential for BIT/BITE and so forth) must be well understood and quantified. Being non-traditional information at early decision making stages does not alter this need. This information has been determined to be key to understanding the total costs of a space transportation system. It is important that any HRST, reusable being the focus, quantify and understand the relationship of certain design features to eventual life cycle costs - development, acquisition and especially operation.

2. The need to quantify, predict and optimize recurring costs as well as other attributes of a concept such as launch on time or operability requires further efforts such as in modeling development. The ability to answer the question “how often can it launch and how many people are required” leads directly to “how much will it cost to operate”. In order to enable successful decision making connected to long term goals information is required to formulate benchmarks that allow predicting the eventual operating costs of potential designs and architectures. This information which establishes a resource that is a result of a design would allow improvements focused on the costs of access to space to be well anchored and therefore more likely to actually succeed in achieving market growth through greater overall affordability.

3. A significant few top features have been determined here based on diverse sets and levels of information and team member backgrounds. Tentatively, it can be derived that an understanding of the complex inter-relationships of these top criteria is key to any strategy for improvement in space transportation affordability. A “cascade” effect for these criteria should be sought for improvements at the component, subsystems, and architecture levels. The intent is to have a ripple through as many of the important, prioritized criteria as possible. This is similar to the approach used in cascading weights to achieve performance gains.

→

Background of the SPST

The Space Propulsion Synergy Team traces it's origins to the Space Propulsion Synergy Group. This group was formed in 1990 to address the findings of the Space Propulsion Technology Symposium held at Penn State University (Bray 1993 and Dankhoff and Hope 1993)[7,9]. These findings included:

- "The lack of a recognized national space propulsion strategy is detrimental to U.S. space programs and international posture"
- "There exists major gaps between technology developers and users, and a means of correcting this is essential"
- "Technology users (i.e. propulsion system developers, producers and operators) should provide their real requirements, and share in technology program planning and funding"

The SPSG eventually became involved in the Access to Space Study[14], and, as the Space Propulsion Synergy *Team*, the X-33 / RLV technology development and demonstration programs.

Positive involvement of the SPST in the future direction of access to space toward low cost, routine operations continues with support to the Highly Reusable Space Transportation Study, the subject of this report.

Currently the membership involved in providing support and insight to the Highly Reusable Space Transportation project includes a diverse group of government, industry and academia. The membership that has been or is currently involved in HRST support activity, such as the development of this guide, includes:

Dana Andrews	Boeing / D&SG Seattle, WA	T- 206-773-1137 **F -6624**
Jim Berry	McDonnell Douglas Huntington Beach, CA	T- 714-896-3557 **F -5807**
Jim Bray	LMMSS MAF, LA	T- 504-257-5536 **F -1210**
Ray Byrd	Boeing Cocoa Beach, FL	T- 407-783-0220 / ext. 309 **F -2712**
Ed Cady	McDonnell Douglas Huntington Beach, CA	T- 714-896-5075 **F -6930**

George Cox	P&W / UTC West Palm Beach, FL	T- 407-796-2887 **F -5099**
Steve D'Alessio	Johns Hopkins Univ., APL Laurel, MD	T- 301-953-6000 / ext. 7810 **F -5937**
Bryan S. DeHoff	Aerospace Technical Services West Chester, OH	T- 513-755-1360 **F -1360**
Walt Dankhoff	SPST Executive Secretary Wash. D.C., AIAA	T- 410-257-0056 **F- 301-855-8332**
Bruce Farner	USAF, Philips Lab Edwards AFB, CA	T- 805-275-5206 **F -5852**
Tom Funicilli	Aerojet CA	T- 916-355-3249 **F -3015**
Dave Goracke	Rocketdyne Canoga Park, CA	T- 818-586-0378 **F -0579**
Jerry Grey	AIAA Wash. D.C.	T- 516-537-3942 **F- 212-595-3184**
Joe Hamaker	NASA / MSFC	T- 205-544-0602 **F -5861**
Joe Haney	Rockwell Downey, CA	T- 310-922-1057 **F -5358**
Ron Hankins	Aerojet CA	T- Retired **F**
Robert Houston	LMMSS MAF, LA	T- 504-257-1510 **F -1210**
Larry Hunt	NASA / LaRC	T- 804-864-3732 **F -8545**
Lee Jones	NASA / MSFC	T- 205-544-7094 **F -3960**
Gary Lee	Boeing / D&SG Seattle, WA (SATWG I/F)	T- 206-773-8964 **F -9070**
Dan Levack	Rocketdyne Canoga Park, CA	T- 818-586-0420 **F -0579**
Scott May	NASA / MSFC	T- 205-544-9525 **F -5861**

Carey McCleskey	NASA / KSC	T- 407-861-3775 **F -0103**
Earl Pansano	LMMSS MAF, LA	T- 504-257-5302 **F -1210**
Russel Rhodes	NASA / KSC	T- 407-861-3874 **F -3036**
John Robinson	Propellant Supply Tech. CO	T- 303-979-8179 **F -1597**
Rick Vargo	McDonnell Douglas FL	T- 407-383-2827 **F -269-6202**
Gordon Woodcock	Boeing Huntsville, AL	T- Retired **F**
Edgar Zapata	NASA / KSC	T- 407-861-3955 **F -3036**

Overview of the SPST Approach

Benefits (Technical), Programmatics (Constraints) and Functions (Performance)

Benefits (Technical)

Affordable / Low Life Cycle Cost Low Recurring Cost Low Cost Sensitivity to Flight Growth Operation and Support Initial Acquisition Vehicle/System Replacement **Dependable** Highly Reliable Intact Vehicle Recovery Mission Success Launch on Time Robustness **Environmental Compatibility** Minimum Effect on Atmosphere Minimum Impact all Sites **Public Support** Benefit GNP Social Perception	**Responsive** Flexible Capacity Operable Vehicle Health Management Ease of Vehicle/System Integration Maintainable Simple Launch on Demand Easily Supportable Resiliency **Safety** Vehicle Safety Personnel and Public Safety Equipment and Facility Safety

Programmatics (Constraints)

During the Technology R&D Phase:	During the Program Acquisition Phase:
Affordable / Low Life Cycle Cost Cost to Develop **Schedule** **Risk** **Dual Use Potential**	**Affordable / Low Life Cycle Cost** Cost to Acquire **Schedule** **Risk** **Technology** **Investor Incentive**

Functions (Performance)

Payload of 30,000 lbm nominal (+/- 10,000 lbm), volume of 15 X 35 ft, to 28.5 degrees and 100 nautical miles nominal altitude. Multiple customers.

Quality Function Deployment (QFD) is a method pioneered by the Japanese in the late 60's as a way of translating consumer demands into design targets. To quote Yoji Akao (Akao 1988)[1]:

> *"With such fast paced change occurring these days, especially in our social and economic environment, many companies are facing rapid changes in industrial structure bought about by the technological innovation and changing consumer trends. These companies are finding that the effort to develop new products is crucial for their survival."*

		Environmental		Safe							Dependable		
QFD Chart for Highly Reusable Space Transportation (Operational Phase)	(Quality Characteristic) **Benefit Criteria**	#pollutive or toxic materials (-)	# acres permanently affected (-)	# of keepout zones (-)	Amount of energy release from unplanned reaction of propellant (-)	# of toxic fluids (-)	# of propulsion sub-systems with fault tolerance (+)	# of confined spaces on vehicles (-)	Amount of response time to initiate safe abort (-)	% of trajectory time available for abort (+)	# of active components required to function including flight operations (-)	# of components with demonstrated high reliability (+)	# of systems requiring monitoring due to hazards (-)
(Demanded Quality)	**List Number**	1	2	3	4	5	6	7	8	9	10	11	12
Attributes	**WEIGHT**												
Affordable / Low Life Cycle Cost													
Low Recurring Cost													
Low Cost Sens. to Flt. Growth	1.83												
Operation and Support	11.44												
Initial Acquisition	4.12												
Vehicle/System Replacement	4.12												
Dependable													
Highly Reliable													
Intact Vehicle Recovery	2.29												
Mission Success	1.72												
Launch on Time	6.86												
Robustness	4.57												
Responsive													
Flexible	2.74												
Capacity	2.29												
Operable													

⇓ ⇓ ...⇒

Part of the matrix for the QFD correlating attributes to measurable criteria

Immediately, one might conclude that the notion of consumers is, for the most part, not relevant to the business of launching payloads to orbit, or at least the situation is not at all similar to a person in the market for a new VCR. This perception is entirely incorrect. In so far as there are customers with demands for better or new products then QFD is fully applicable. The business of translating these demands from the vague and qualitative (and not very useful) to the more specific and material is custom made for a method such as QFD.

A QFD has certain requirements. Customer definition must be given great thought. Teams must be synergistic. The qualities of our systems, attributes such as responsiveness or flexibility, must be fully explored, defined and related. Possible measures of these qualities must be determined. Finally, the relation of the specific measures to qualitative attributes must be explored, reasoned out, and weighted. The process is methodical and with relentless pressure yields the insights leading to the all important design targets that eventually must guide product development.

Besides countless information on the World Wide Web (searches on "QFD" will yield a variety of papers, organizations and other information) one book suggested here for further reading is the translation from the Japanese of Yoji Akao's "Quality Function Deployment - Integrating Customer Requirements into Product Design"[1].

The SPST approach to functional or performance requirements is a simplified “gate”. For purposes of developing the criteria contained in this guide, which is strategic in nature, and understanding the interrelationships and priorities, the specific details on the performance of particular concepts and technologies is not required. However, in determining the transportation system performance closure or compliance there must be a growth or technology margin included at this early stage. Further detailed steps in the technology evaluation process requires that performance aspects of potential technologies, or whole transportation systems built from these technologies, be one of the basic building blocks in the decision making process.

One such example applies to rocket based combined cycle (RBCC) type vehicles. The following is one possible approach to maintaining a necessary tracking of the ability of a concept to reach closure and satisfy functional requirements.

Possible spreadsheet, with entries listed at one second intervals along the flight trajectory:

t	time, s
u	velocity, ft/s
Z	altitude, ft
X	downrange, ft
M	Mach number
W	weight, lbf
q	dynamic pressure, lbf/ft^2
θ	flight path angle, deg
α	angle of attack, deg
T	thrust, lbf
L	lift, lbf
D_0	drag at zero lift, lbf
D_L	induced drag, lbf
D	total vehicle drag, lbf
I_f	engine specific impulse, s
I_{eff}	vehicle specific impulse = $I_f(1\text{-}D/T)$
w_e	engine airflow rate, lbm/s
w_{H2}	hydrogen flow rate, lbm/s
w_{O2}	oxygen flow rate, lbm/s
ER	overall engine equivalence ratio
a	vehicle acceleration, ft/s^2

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Acronyms and Abbreviations

A/C	Air Conditioning
Ai	Availability, Inherent
APU	Auxiliary Power Unit
BIT	Built in Test
BITE	Built in Test Equipment
CAPSS	Computer Aided Planning and Scheduling System
CIL	Critical Items List
c/o	Checkout
CoFR	Certificate of Flight Readiness
DDT&E	Design, Development, Test and Engineering
DMES	Dimethylethoxysilane
ECLSS	Environmental Control and Life Support System
EMA	Electromechanical Actuator
ET	External Tank
FMEA	Failure Mode Effects Analysis
GH2	Gaseous Hydrogen
GHe	Gaseous Helium
GLOW	Gross Lift Off Weight
GN2	Gaseous Nitrogen
GNP	Gross National Product
GO2	Gaseous Oxygen
GPSS	Ground Processing Scheduling System
GSE	Ground Support Equipment
GUCP	Ground Umbilical Carrier Plate
H2	Hydrogen
HCF	High Cycle Fatigue
HCFC	Hydrochlorofluorocarbons
HGDS	Hazardous Gas Detection System
Hp	Horsepower
HRST	Highly Reusable Space Transportation
I/F	Interface
Isp	Specific Impulse
LCC	Life Cycle Cost
LCF	Low Cycle Fatigue
LDT	Logistics Down Time
LH2	Liquid Hydrogen
LHe	Liquid Helium
LO2	Liquid Oxygen
LOX	Liquid Oxygen
LRU	Line Replaceable Unit

MCC	Main Combustion Chamber
MMH	Monomethylhydrazine
MPS	Main Propulsion System
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
N2O4	Nitrogen Tetroxide
NDE	Non-Destructive Test
NH3	Ammonia
nm	Nautical mile
O2	Oxygen
OMRS	Operations Maintenance Requirement Specification
OMS	Orbital Maneuvering System
OPF	Orbiter Processing Facility
OSAMS	Operation Simulation and Analysis Modeling System
PA	Program Acquisition
PCA	Precision Cleaning Agent
PDR	Preliminary Design Review
PR	Problem Report
PRACA	Problem Reporting and Corrective Action
PVT	Pressure, Volume, Temperature
QFD	Quality Function Deployment
R&D	Research and Development
RBCC	Rocket Based Combined Cycle
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RM&S	Reliability, Maintainability, and Supportability
ROM	Rough Order of Magnitude
RP-1	Rocket Propellant, Kerosene
SCAN	Shuttle Connector Analysis Network
SPST	Space Propulsion Synergy Team
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engine
SSTO	Single Stage to Orbit
TRL	Technology Readiness Level
TSM	Tail Service Mast
TVC	Thrust Vector Control
VHM	Vehicle Health Management